Natural Resources Canada / Ressources naturelles Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 7976

2015 Report of activities for High Arctic Large Igneous Province (HALIP) GEM 2 Western Arctic Region Project

K. Dewing (Editor)

2015

Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 7976

2015 Report of activities for High Arctic Large Igneous Province (HALIP)
GEM 2 Western Arctic Region Project

K. Dewing (Editor)

Geological Survey of Canada, 3303-33rd Street NW, Calgary, Alberta

2015

doi:10.4095/297367

Recommended citation
Dewing, K. (ed.), 2015. 2015 Report of activities for High Arctic Large Igneous Province (HALIP) – GEM 2 Western Arctic Region Project; Geological Survey of Canada, Open File 7976, 61 p. doi:10.4095/297367

REPORT OF ACTIVITIES FOR HALIP

INTRODUCTION TO THE HALIP ACTIVITY

M.-C. Williamson[1]

[1.] Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario
(email: Marie-Claude.Williamson@Canada.ca)

FOREWORD

The Geo-mapping for Energy and Minerals (GEM) program provides public geoscience that will set the stage for long-term decision making related to investment in resource development. GEM supports exploration for energy and mineral resources through improved mapping and modern geoscience information in areas of resource potential, and enables northern communities and regulators to make informed decisions about their land and economy. Building upon the success of its first five years, GEM was renewed until 2020 to continue producing publically available, regional-scale geoscience knowledge in Canada's North.

During the summer 2014, GEM's research program launched 14 field activities that include geological, geochemical and geophysical surveying (Figure 1). These activities have been undertaken in collaboration with provincial and territorial governments, northerners and their institutions, academia and the private sector.

INTRODUCTION

The Sverdrup Basin is a northeast-trending, intracratonic basin that extends along the Canadian Arctic continental margin from the northern tip of Ellesmere Island to Prince Patrick Island. Its modern extent is 1,300 km long and 400 km wide, and contains up to 13 km of Carboniferous to Tertiary strata (Embry, 2011). The volcanic terrain of Cretaceous age exposed in the east-central Sverdrup Basin is the focus of an activity approved for the second phase of NRCan's Geo-Mapping for Energy and Minerals Program[1] (Western Arctic Region Project).

OBJECTIVES

A key objective of this activity, from 2014 to 2017, is to assess the potential on Axel Heiberg Island and Ellesmere Island for Ni-Cu-PGE deposits. 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.

GEOLOGIC CONTEXT

Volcanic rocks, dyke swarms, and sills of Cretaceous age exposed across the High Arctic are referred to collectively as the Canadian portion of the High Arctic Large Igneous Province (HALIP; Figure 2). The igneous rocks are predominantly basaltic, a characteristic of large igneous provinces (LIPs) associated with continental break up (Ernst, 2014; Jowitt et al., 2014). The Canadian portion of HALIP is the most important magmatic event associated with the tectonic reactivation of the Sverdrup Basin and opening of the Arctic Ocean in the Early Cretaceous (e.g. Embry and Osadetz, 1988; Villeneuve and Williamson, 2006; Vogt et al., 2006; Ernst and Bleeker, 2010; Døssing et al., 2013).

The HALIP exposed in the east-central Sverdrup Basin presents most of the attributes of prospective Ni-Cu-PGE continental flood basalt provinces (Williamson and MacRae, 2001). Flood basalts and volcanic-intrusive complexes were emplaced during an Early to earliest Late Cretaceous rifting event (Stephenson et al., 1987). Geochemical studies suggest that the sills and dykes intruded in areas close to the Mesozoic depocentre interacted with evaporites on a regional scale. A recent lithogeochemical study concludes that the Strand Fiord Formation basalts exposed on Axel Heiberg Island are prospective for Ni-Cu-PGE (Jowitt et al., 2014). Further, the intrusion of magmatic rocks within the east-central Sverdrup Basin has been demonstrated to influence the thermal structure of the basin and the maturation of petroleum (Jones et al., 2007), a result that is consistent with studies of the HALIP in other parts of the Arctic. Characterizing the extent, and the timing of

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

different volcanic and intrusive episodes is a key component in models of basin subsidence and development applied to the Western Arctic region, with implications for offshore studies of the polar continental margin.

The HALIP activity will provide 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.

METHODOLOGY

Mineralogy and Geochemistry

In Year 1 of the activity, geochemical analyses were carried out on ~150 legacy samples previously archived at the Department of Earth Sciences, Dalhousie University (Halifax, Nova Scotia). In Year 2, the database will be expanded to include samples collected during the 2015 field season (eruptive and intrusive rocks, bentonites, and gossans). Field work is guided by previous work that suggests the Ni-Cu-PGE prospectivity of tholeiitic rocks exposed on Axel Heiberg Island (Williamson and MacRae, 2001; Jowitt et al., 2014).

The spatial and temporal evolution of the volcanic-intrusive system and implications for magma 'fertility' is still poorly understood. Analysis of legacy samples illustrates the change in the composition of HALIP igneous rocks from tholeiitic to ferrobasaltic and alkaline (Figure 3). The most prospective rocks are tholeiitic as demonstrated by the Ni depletion trend shown on Figure 4. A plot of Cu/Zr vs. Ti/Zr (Figure 5) also supports the affinity of tholeiitic basalts in the Strand Fiord Formation with geochemical fields for Tk-and Nd-basalts from the Norils'k region. Additional samples from 2015 will augment this dataset.

Bedrock Mapping

Field work in Year 2 of the activity will focus on HALIP-related stratigraphy and physical volcanology (volcanic rocks, volcaniclastic deposits, sills, dykes, breccias in proximity of evaporite domes, gossans), diapirs, and local architecture of volcanic-intrusive complexes. Resolving the nature of these complexes across the entire study area is essential to further our understanding of Ni-Cu-PGE prospectivity in this part of Nunavut.

Geochronology

Targeted geochronological studies of key units in the study area will lead to a calibrated stratigraphic framework and the timing of principal magmatic events where knowledge gaps exist.

Thermochronology

Thermochronological studies will clarify the timing of hydrocarbon maturation relative to magmatism and evaporite diapirism.

Stream Sediment Surveys

Reconnaissance regional drainage survey was carried out in July 2015 in the central-eastern part of Axel Heiberg Island in four geologically distinct areas located between Whitsunday Bay and Lightfoot River.

CONCLUSIONS

The main objective of the HALIP activity is to determine the impact of magmatism on mineral and hydrocarbon potential in east-central Sverdrup Basin. New geochemical analyses obtained in Year 1 were used as a guide for field planning. The 2015 field season will include (1) detailed mapping and sampling of sills and dykes with a special focus on volcanic-intrusive complexes; (2) the collection of key samples for mineralogical, geochemical, thermochronological and geochronological studies; and (3) detailed stream sediments surveys to test the data and interpretations reported by McNeil et al. (2015).

ACKNOWLEDGMENTS

The author thanks Thomas Duffett, Gordon Oakey and Andrew MacRae for help with the Dalhousie University Arctic Expedition samples. Jacques Pinard, Pat Hunt, Stéfane Prémont, Christine Deblonde and Guy Buller provided invaluable assistance with sample preparation, laboratory analyses and information management. Benoit Saumur is thanked for updating the geochemical diagrams of Williamson and MacRae (2001).

REFERENCES

Alvey, A., Gaina, C., Kusznir, N.J., and Torsvik, T.H., 2008, Integrated crustal thickness mapping and plate reconstructions for the high Arctic. Earth and Planetary Science Letters, v. 274, p. 310-321.

Buchan, K.L., and Ernst, R.E., 2006, Giant dyke swarms and the reconstruction of the Canadian Arctic Islands, Greenland, Svalbard, and Franz Josef Land, in Hanski, E., Mertanen, S., Rämö, T., and Vuollo, J., eds., Dyke swarms: Time markers of crustal evolution: London, Taylor & Francis/Balkema, p. 27–48.

Embry, A., 2011. Chapter 36: Petroleum prospectivity of the Triassic–Jurassic succession of Sverdrup Basin, Canadian Arctic Archipelago; Geological Society of London, Memoirs, v. 35, p. 545-558. doi:10.1144/M35.36

Embry, A.F., and Osadetz, K.G., 1988, Stratigraphy and tectonic significance of Cretaceous volcanism in Queen Elizabeth Islands, Canadian Arctic Archipelago. Canadian Journal of Earth Sciences, v. 25, p. 1209–1219.

Ernst, R. E., 2014. Large Igneous Provinces; Cambridge University Press, 653 p.

Ernst, R.E., and Bleeker, W., 2010, Large igneous provinces (LIPs), giant dyke swarms, and mantle plumes: significance for breakup events within Canada and adjacent regions from 2.5 Ga to the Present: Canadian Journal of Earth Sciences, v. 47, p. 695–739.

Fedorenko, V.A., Lightfoot, P.C., Naldrett, A.J., Czemanske, G.K., Hawkesworth, C.J., Wooden, J.L., and Ebel, D.S., 1996, Petrogenesis of the flood-basalt sequence at Norils'k, North Central Siberia. International Geology Review, v. 38, p. 99-135.

Jones, S.F., Wielens, H., Williamson, M.-C., and Zentilli, M., 2007. Impact of magmatism on hydrocarbon systems of the Sverdrup Basin, Canadian Arctic Islands, Nunavut; a numerical modelling experiment, Journal of Petroleum Geology, Vol. 30, no. 3, pp. 237-255.

Jowitt, S.M., Williamson, M.-C. and Ernst, R.E., 2014. Geochemistry of the 130 to 80 Ma Canadian High Arctic Large Igneous Province (HALIP) Event and Implications for Ni-Cu-PGE. Economic Geology, v. 109, no. 2, p. 281-307.

Lightfoot, P.C., Hawkesworth, C.J., Hergt, J., Naldrett, A.J., Gorbachev, N.S., and Fedorenko, V.A., 1993, Remobilization of the continental lithosphere by a mantle plume: major-, trace element and Sr-, Nd- and Pb-isotope evidence from picritic and tholeiitic lavas of the Norils'k District, Siberian Trap, Russia. Contributions to Mineralogy and Petrology, v. 114, p. 171-188.

McNeil, R.J., Day, S.J.A., and Williamson, M.-C., 2015. Stream sediment and water geochemical study, Axel Heiberg Island, Nunavut, Canada, *in* Environmental and Economic Significance of Gossans, (ed.) M.-C. Williamson; Geological Survey of Canada, Open File 7718, p. 85-96.

Stephenson, R.A., Embry, A.F., Nakiboglu, S.M. and Hastaoglu, M.A., 1987. Rift-initiated Permian to Early Cretaceous subsidence of the Sverdrup Basin, *in* Sedimentary Basins and Basin-Forming Mechanisms; Canadian Society of Petroleum Geologists, Memoir 12, p. 213-231.

Villeneuve, M., and Williamson, M.-C., 2006, 40Ar-39Ar dating of mafic magmatism from the Sverdrup Basin magmatic province, in Scott, R.A., and Thurston, D.K., eds., Proceedings of the Fourth International Conference on Arctic Margins, 30 September–3 October, Dartmouth, Nova Scotia: Anchorage, USA, Department of the Interior, p. 206–215.

Vogt, P.R., Jung, W.Y., Jakobsson, M., Mayer, L., and Williamson, M.-C., 2006. The Alpha-Mendeleev Magmatic Province, Arctic Ocean: A new synthesis, Eos Trans. AGU, Vol. 87, no. 36, Jt. Assem. Suppl., Abstract # OS31A-02.

Williamson, M.-C., 1988, The Cretaceous igneous province of the Sverdrup basin, Canadian arctic: Field relations and petrochemical studies. Unpublished Ph.D. thesis, Dalhousie University, Halifax, Canada, 417 p.

Williamson, M-C., and MacRae, R.A., 2001. Mineralization potential in volcanic rocks of the Strand Formation and associated intrusions, Axel Heiberg Island, Nunavut, Canada. Report of Project in Development, Geological Survey of Canada (Atlantic): 26 p.

Williamson, M.-C., Oakey, G., and Okulitch, A.V., 2007. Geological, geophysical, and structural signatures of intrusive complexes in the Sverdrup Basin Magmatic Province, Northern Ellesmere Island, Canada, ICAM V - 5th International Conference on Arctic Margins, 3-7 September, 2007, Tromsø, Norway.

Williamson, M.-C., McNeil, R.J., Day, S.J.A., McCurdy, M.W., Rainbird, R.H., and Grunsky, E.C., 2015. Environmental impact of gossans revealed by orientation surveys for base metals in the Canadian Arctic Islands, in Environmental and Economic Significance of Gossans, (ed.) M.-C Williamson; Geological Survey of Canada, Open File 7718, p. 74-84.

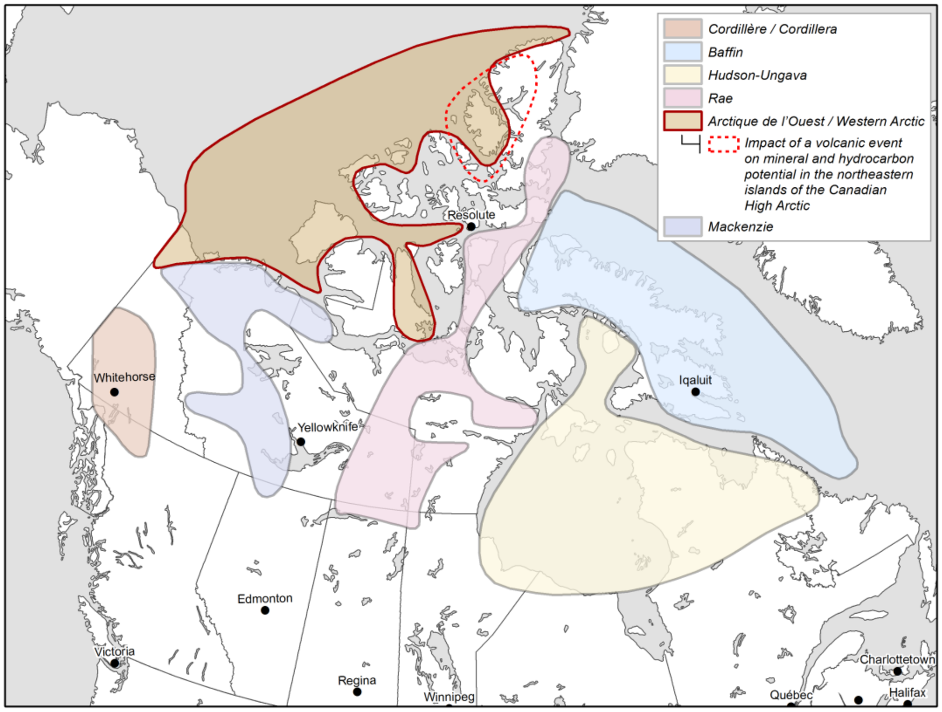

Figure 1. Regional map of the GEM 2 activities (2014-2017) showing the area covered by the Western Arctic Region Project. The area covered by the HALIP activity is shown by red dots.

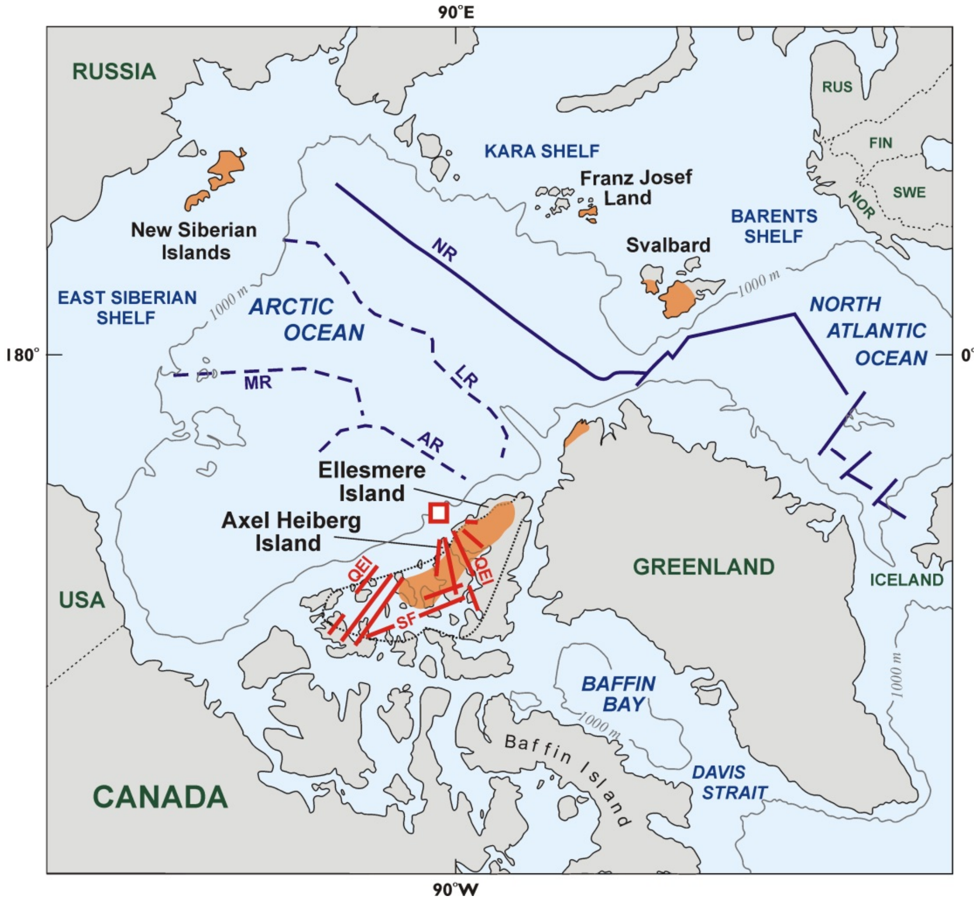

Figure 2. Map of the circum-Arctic region. Areas in orange show the general distribution of exposures of the HALIP (after Jowitt et al., 2014). The Canadian portion of the HALIP occurs within the Sverdrup Basin, the outline of which is identified with a dotted line. The general pattern of the Queen Elizabeth Island dyke swarm (QEI) and the potentially coeval Surprise Fiord dyke swarm (SF) are indicated in red (after Embry and Osadetz, 1988; Buchan and Ernst, 2006). The red square indicates the focal point of these dykes and the possible location of a mantle plume associated with the HALIP event (after Buchan and Ernst, 2006). The crustal thickness of the submarine portion of the High Arctic is after Alvey et al. (2008) and was contoured at a thickness of 20 km: portions that are >20 km thickness are a darker grey, and those that are less than 20 km thick are lighter grey. The crustal structure highlights the geometry of submarine ridges of the Arctic Ocean: AR – Alpha Ridge; MR – Mendeleev Ridge; LR – Lomonosov Ridge. Alpha Ridge exhibits evidence of Cretaceous magmatism coeval with that of the Sverdrup Basin.

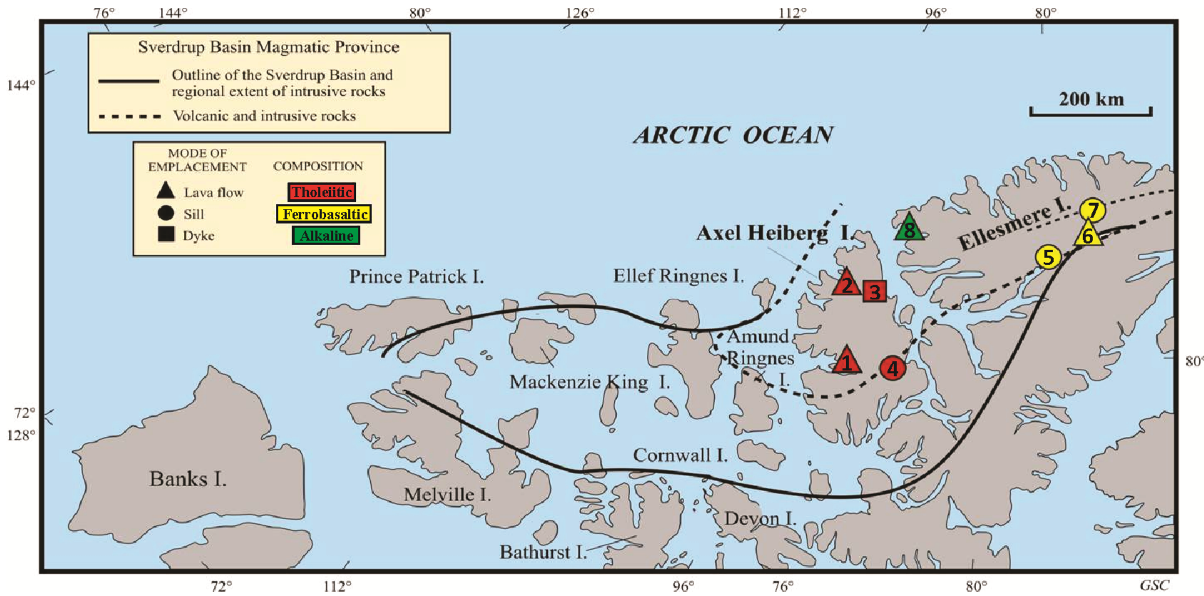

Figure 3. Map of the Canadian Arctic Islands showing HALIP study areas on Axel Heiberg Island and northern Ellesmere Islands. Symbols for mode of emplacement and composition are also used in Figures 4 and 5. [1] Strand Fiord-Expedition Fiord region; [2] Bunde Fiord; [3] Lightfoot River; [4] Buchanan Lake; [5] Tanquary Fiord; [6] Lake Hazen; [7] Piper Pass; [8] Emma Fiord. Modified from Villeneuve and Williamson (2006).

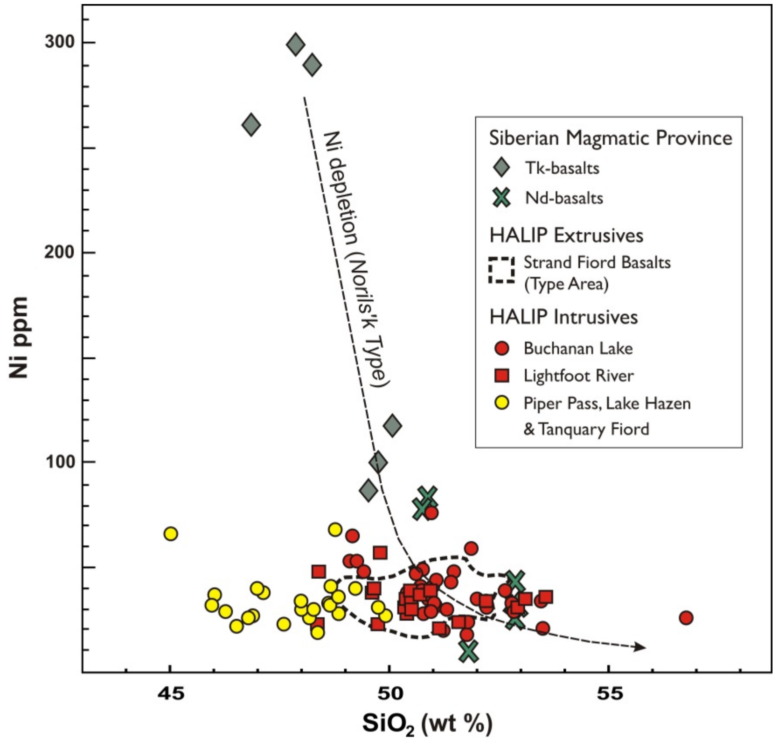

Figure 4. Map of prospectivity of the HALIP based on whole rock Ni vs. SiO2 (after Williamson and MacRae, 2001). Data from Norils'k Talnakh are from Lightfoot et al. (1993) and Fedorenko et al. (1996). Data from the HALIP are from Williamson (1988). Symbols and colour scheme keyed to Figure 3.

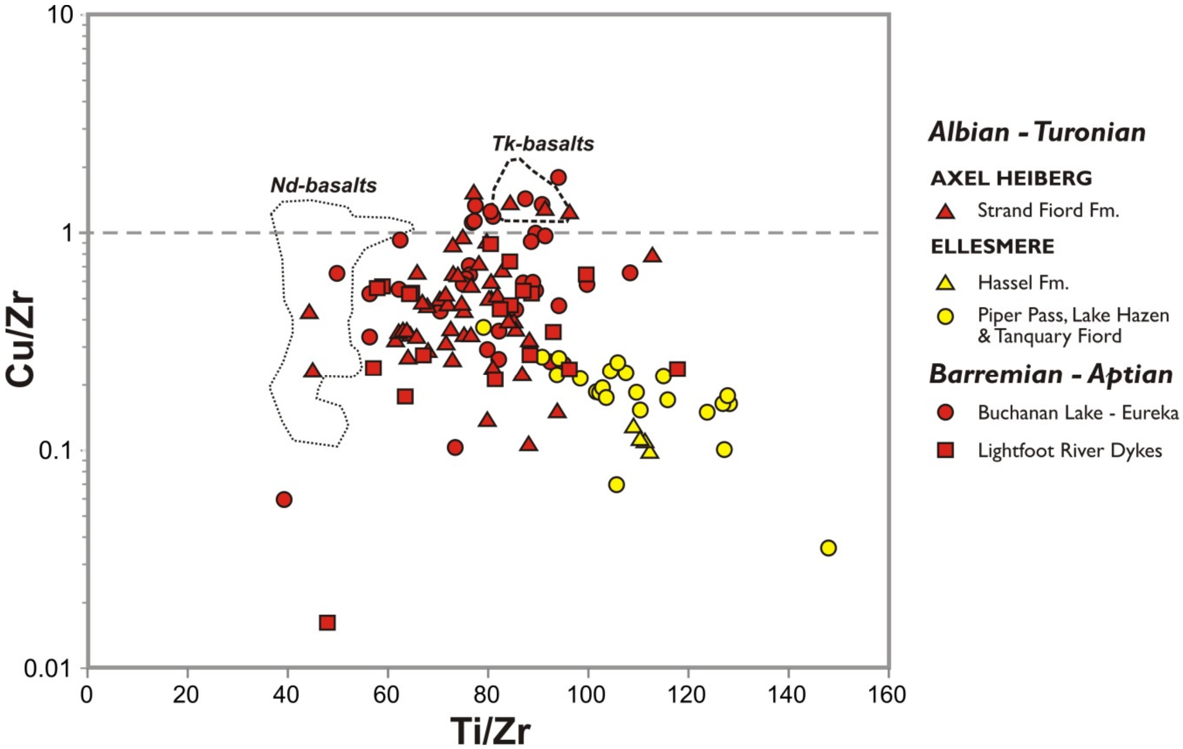

Figure 5. Prospectivity of the HALIP based on trace element contents. Data are from Williamson (1988). Fields for Cu/Zr vs. Ti/Zr. Fields of Tk-basalt and Nd-basalt are from are from Lightfoot et al. (1993). Symbols and colour scheme keyed to Figure 3.

HALIP LEGACY SAMPLES, PART I – THE OTTAWA COLLECTION

B.-M. Saumur[1]
[1]. Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario
(email: benoit-michel.saumur@canada.ca)

INTRODUCTION

The GEM 2 HALIP project benefits from the availability of samples of basalts and gabbros of the HALIP and associated country rocks, collected between 1983 and 1992, at Axel Heiberg and Ellesmere islands. These rocks have been in storage for over 25 years. At the start of this project in 2014 a digital database containing information on the rocks (e.g., rock types, units, formations), locations (e.g., field area, coordinates) and available data (mineral analyses, geochemical analyses) did not exist. Nevertheless, it was recognized that the collections represent a valuable asset to this project, since in extremely remote areas such as the Canadian Arctic it is much more efficient and cost effective to analyse (or reanalyze) previously collected samples than to conduct new fieldwork in a previously sampled area. The analysis of HALIP legacy collections is therefore critical to the success of the GEM 2 HALIP project, and the description of this collection will benefit all collaborators on the project. Between September 2014 and June 2015, this compilation of existing samples helped constrain spatial gaps in sample coverage and areas of new fieldwork for the summer of 2015. Furthermore, pre-fieldwork preparation included geochemical and isotopic analysis of several samples from these collections (Williamson, this volume; Bédard, this volume), which will assist in enhancing regional geochemical coverage for the Canadian HALIP.

Numerous studies have focused on the geology of the area, starting with the mapping of *Operation Franklin* (Fortier, 1963), and subsequent work focussing more specifically on Cretaceous extrusive and intrusive igneous rocks (e.g., Ricketts et al., 1985; Osadetz and Moore, 1988; Embry and Osadetz, 1988). Unfortunately, sample collections stemming from such work are not available. Nevertheless, the distribution and spatial coverage of units of the HALIP can be constrained from such work; in particular, Embry and Osadetz (1988) highlighted the distribution of Cretaceous volcanic rocks, and the many maps compiled by R. Thorsteinsson (e.g., Thorsteinsson, 1971a; b; Thorsteinsson and Trettin, 1971; 1972) indicate that Cretaceous dykes crop out at numerous localities on Axel Heiberg and Ellesmere Islands. Such work allows us to identify areas that are not represented in our legacy collections and constrain sites of future fieldwork.

Two legacy collections, consisting mostly of rocks of the Canadian HALIP, are available for GEM 2. The first is located in Ottawa and consists of samples collected between 1983 and 1985 by M.-C.Williamson during the course of her Ph.D. studies at Dalhousie University (Williamson, 1988). A second legacy collection, currently located at Dalhousie University, consists of samples collected by G. Muecke between 1984 and 1992; this collection is topic of a separate contribution (Saumur et al., this volume). Hereafter, we focus solely on the 1983-1985 collection located in Ottawa.

Background

During the course of her Ph.D. studies, MCW conducted three field excursions: the 1983 season was spent on Axel Heiberg Island; the 1984 season was spent at various locations on Ellesmere Island; the 1985 season was spent at several localities on both islands. Upon the completion of the Ph.D. project, the rocks were stored at the Earth Sciences Department of Dalhousie University. These samples were transferred to GSC Ottawa in 2012 (Williamson et al., 2012).

Previous analyses of samples from the 1983-1985 collection include whole rock, trace element and mineral analyses by Williamson (1988). Selected samples of the collection were analysed by Ernst and Buchan (2010) for whole rock, trace element and precious metals; these analyses formed the basis of an assessment of the Ni-Cu-PGE prospectivity of the HALIP by Jowitt et al. (2014). Avison (1987) performed ^{40}Ar-^{39}Ar dating (biotite, plagioclase, whole rock) on seven samples from the collection, and whole rock ^{40}Ar-^{39}Ar dating on six samples of the database was reported by Villeneuve and Williamson (2006).

Other available ages for rocks of the HALIP (via several methods, i.e., U-Pb zircon, K-Ar whole rock) are provided in Villeneuve and Williamson (2006). More recently, additional data are available from intrusive and extrusive rocks of NW Ellesmere (Estrada and Henjes-Kunst, 2013), the Lake Hazen/Piper Pass area of NE Ellesmere (Estrada, 2014) and Ellef Ringnes islands (Evenchick et al. 2015). A comprehensive compilation is available internally at the GSC (B. Davis, pers. comm.).

Sample inventory & database development

The inventory of the collection was initiated by BMS in September 2014. Prior to this inventory no digital and updatable database describing the collection was available. The new database represents a working tool that is meant to be updated as new work is performed and new information is available on the samples. The database was constructed in such a way to utilize the 'filter' function of *EXCEL*, which allows the user to quickly locate samples with certain data available or attributes (e.g., available geochemistry, mineral analyses) or emplaced in a certain manner (e.g., dykes, sills, flows). The information that was added in the database for each sample, from information available in field notes, diaries, georeferenced air photos and publications is detailed in Table 1. Work is ongoing on the database; once completed it will be presented in a subsequent Open File Report.

A total of 499 samples were identified and included in the database. In the samples inventoried, 292 are from Axel Heiberg Island (including 4 samples from Bjarnason Island) and 207 are from Ellesmere Island.

Regional sample coverage & gaps in coverage

The geographic coverage available from the samples in the collection consists of nine localities and several sub-localities summarized in Figure 1 and Table 2. Sub-localities where extrusive rocks were sample generally represent cross-sections of volcano-sedimentary sequences were measured and sampled. Localities where several intrusive rocks (dikes, sills) were sampled can represent field areas of relatively larger aerial extent. Furthermore, based on the samples available in the 1983-1985 legacy collection and results from other previous studies, Figure 1 highlights areas where gaps in geochemistry occur; these are further summarized in Table 3.

Fieldwork in the summer of 2015 concentrated in three areas that represent spatial gaps in coverage (Fig. 1): Agate Fiord north (Plateau Lake), Middle Fiord north and Surprise Fiord west. The field team consists of BMS, M.-C. Williamson and C. Evenchick. Further rationale for fieldwork in these areas is discussed in Williamson (this volume).

New geochemical analyses on legacy samples

Table 2 indicates the number of rocks, per locality, that were submitted for whole rock and trace element analyses between December 2014 and February 2015. Geochemistry will be obtained by AES and ICP-MS at the facilities of the INRS (Québec City), under the guidance of Stéfane Prémont. Three main factors were considered when determining what samples to analyze within the GEM 2 activity: (1) a focus on rocks of the Strand Fiord Formation, which are the most prospective of the HALIP in terms of Ni-Cu-PGEs (e.g., Williamson and MacRae, 2001) and intrusive complexes (i.e., sill-dyke complexes) of the HALIP; (2) maximizing regional geochemical coverage, specifically for sills and dykes; (3) obtaining updated data from selected complete lava sections; (4) the analysis of previously unanalysed samples.

A total of 146 samples were submitted for analysis (137 from this collection, plus 9 from saucer sills and mafic units of Ellef Ringnes Island; Evenchick et al., 2015).

REFERENCES

Avison, H.A., 1987, 40Ar/39Ar age studies of mafic volcanics from the Sverdrup Basin, Arctic Canada.

B.Sc. Honours thesis (unpublished), Dalhousie University, Halifax, 88 pp.
Bédard, J.H., 2015, Regional study of HALIP sill geochemistry and economic potential, *in* Dewing, K. (ed.) Report of activities for High Arctic Large Igneous Province (HALIP) - GEM 2 Western Arctic Region Project; Geological Survey of Canada Open File 7976, p. 20-23
Embry, A.F., and Osadetz, K.G., 1988, Stratigraphy and tectonic significance of Cretaceous volcanism in Queen Elizabeth Islands, Canadian Arctic Archipelago. Canadian Journal of Earth Sciences, v. 25, p. 1209–1219.
Ernst, R.E. and Buchan, K.L., in collaboration with L.B. Aspler, W.R.A. Baragar, , M.T. Corkery, A. Davidson, R.F. Emslie, W.F. Fahrig (archives), S.S. Gandhi, J. Goutier, H.C. Halls, M.A. Hamilton, J.Hanes, B.A. Kjarsgaard, A.N. LeCheminant, C. Palmer, J.A. Percival, A. Peterson, W.C. Phinney, H. Sandeman, M.C. Smyk, and M.-C. Williamson, 2010, Geochemistry database of Proterozoic mafic-ultramafic magmatism in Canada, Geological Survey of Canada Open File 6016, 1 CD-ROM. doi:10.4095/261831
Estrada, S., Piepjohn, K., Henjes-Kunst, F. and von Gosen, W., 2006, Geology, Magmatism and Structural Evolution of the Yelverton Bay Area, Northern Ellesmere Island, Arctic Canada. Polarforschung, v. 73, p. 59-75.
Estrada, S. and Henjes-Kunst, F, 2013, 40Ar–39Ar and U–Pb dating of Cretaceous continental rift-related magmatism on the northeast Canadian Arctic margin. Zeitschrift der Deutschen Gesellschaft für Geowissenschaften (German Journal of Geosciences), v.164, p.107–130.
Estrada, S., 2014, Geochemical and Sr-Nd isotope variations within Cretaceous continental flood-basalt suites of the Canadian High Arctic, with a focus on the Hassel Formation basalts of northeast Ellesmere Island. International Journal of Earth Science (Geol Rundsch), doi:10.1007/s00531-014-1066-x
Evenchick, C.A., Davis, W.J., Bédard, J.H., Hayward, N., and Friedman, R.M., 2015, Ages of magmatism in central Sverdrup Basin from volcanogenic rocks, geochronology, and palaeo-depths of saucer-shaped sills. Geological Society of America Bulletin, v. 127, p. 1366-1390.
Fortier, Y.O., 1963, Geology of the North-central Part of the Arctic Archipelago, Northwest Territories, (Operation Franklin); Geological Survey of Canada, Memoir 320, 671 p. doi:10.4095/100547
Hachkowski, C., 2011, Geochemistry and isotopic analysis of mafic dykes from the Raanes Peninsula, Ellesmere Island, Nunavut, Canada. B.Sc. thesis, Carleton University, 101 pp.
Jowitt, S.M., Williamson, M.-C. and Ernst, R. E., 2014, Geochemistry of the 130 to 80 Ma Canadian High Arctic Large Igneous Province (HALIP) Event and Implications for Ni-Cu-PGE. Economic Geology, v. 109, no. 2, p. 281-307.
Osadetz, K.G., and Moore, P.R., 1988, Basic volcanics in the Hassel Formation [Mid-Cretaceous] and associated intrusives, Ellesmere Island, district of Franklin, Northwest Territories; Geological Survey of Canada, Paper 87-21, 19 p., doi:10.4095/126101
Ricketts, B., Osadetz, K.G. and Embry, A.K., 1985, Volcanic style in the Strand Fiord Formation (Upper Cretaceous), Axel Heiberg Island, Canadian Arctic Archipelago. Polar Research, v. 3, p. 107-122.
Saumur, B.-M., Williamson, M.-C., and Evenchick, C.A., 2015a, Volcanic-intrusive complexes of western Axel Heiberg Island, *in* Dewing, K. (ed.) Report of activities for High Arctic Large Igneous Province (HALIP) - GEM 2 Western Arctic Region Project; Geological Survey of Canada Open File 7976, p. 31-33.
Saumur, B.-M., Williamson, M.-C., Muecke, A.L, and Muecke, G.K., 2015b, HALIP Legacy Samples, Part II – The Dalhousie University Collection, *in* Dewing, K. (ed.) Report of activities for High Arctic Large Igneous Province (HALIP) - GEM 2 Western Arctic Region Project; Geological Survey of Canada Open File 7976, p. 17-19.
Thorsteinsson, 1971a, Geology, Middle Fiord, District of Franklin, Geological Survey of Canada, "A" Series Map 1299A, 1 sheet doi:10.4095/109124
Thorsteinsson, 1971b, Geology, Haig-Thomas Island, District of Franklin, Geological Survey of Canada, "A" Series Map 1303A; 1 sheet, doi:10.4095/109126
Thorsteinsson, R., and Trettin, H.P., 1971, Geology, Tanquary Fiord, District of Franklin, Geological Survey of Canada, "A" Series Map 1306A; 1 sheet, doi:10.4095/109129
Thorsteinsson, R., and Trettin, H.P., 1972, Geology, Bukken Fiord, District of Franklin, Geological Survey of Canada, "A" Series Map 1310A; 1 sheet, doi:10.4095/109132.
Villeneuve, M. & Williamson, M.-C., 2006, ^{40}Ar-^{39}Ar dating of mafic magmatism from the Sverdrup Basin Magmatic Province, *in* R.A. Scott and D.K. Thurston (eds.), Proceedings of the Fourth International conference on Arctic margins, OCS study MMS 2006-003, U.S. Department of the Interior: 206-215.
Williamson, M.-C., 1988, The Cretaceous Igneous Province of the Sverdrup Basin, Canadian Arctic: field relations and petrochemical studies. Ph.D. thesis, Dalhousie University, Halifax, Canada.
Williamson, M.-C. & MacRae, R.A., 2001, Mineralization potential in volcanic rocks of the Strand Formation and associated intrusions, Axel Heiberg Island, Nunavut, Canada. Report for Industry (Project in Development) Geological Survey of Canada (Atlantic): 26 p.
Williamson, M.-C., Oakey, G., Harris, J., and Bédard, J., 2012, Intrusive complexes of the east-central Sverdrup Basin (High Arctic) Large Igneous Province have Ni-Cu-Cr-PGE potential. ESS-GEM Scientific and Technical Panel – Final Report: 118.
Williamson, M.-C. 2015, Introduction to the HALIP Activity, *in* Dewing, K. (ed.) Report of activities for High Arctic Large Igneous Province (HALIP) - GEM

2 Western Arctic Region Project; Geological Survey of Canada Open File 7976, p. 2-8.

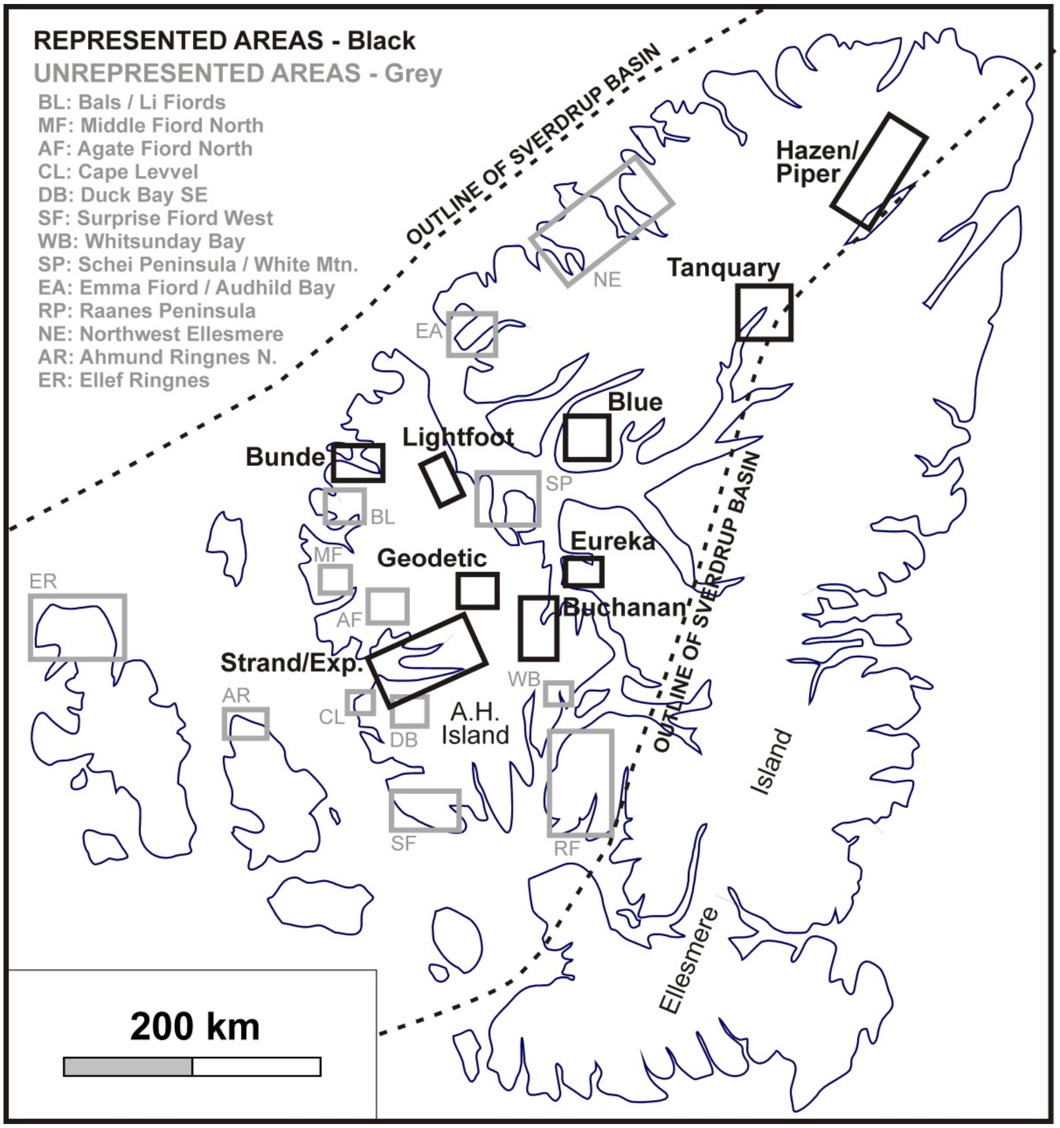

Figure 1: Map of Axel Heiberg and Ellesmere Islands highlighting the localities that are represented in the 1983-85 legacy database. The outline of the Sverdrup Basin is from Embry and Osadetz (1988).

TABLES

SAMPLE ATTRIBUTE or METADATA	SOURCE	DESCRIPTION
Coordinates (Lattitude, Longitude)	W; EB; Airphotos	All samples from MCW's Ph.D. studies have location information (latitude, longitude) that can be extracted from field notes and air photos..
Rock/Emplacement Type	W, Field Notes	Rocks or emplacement types are indicated. For the purposes of this project, these are broken down into five simplified categories: flow, dyke, sill, sedimentary, volcaniclastic.
Additional Location and Stratigraphic Information	W, Field Notes	The name of the locality where the work was carried out is indicated in the database. When available from MCW's field notes, information on Stratigraphy for extrusive and sedimentary rocks (i.e., Isachsen, Strand Fiord, Hassel) is included. The "Unit" column indicates information stratigraphy within the context of a given locality; it may include flow numbers (Flow 1, Flow 2), sill/dyke numbers (Sill Q/ Dyke J) and so on.
Storage Information	Result of Inventory	Samples can be located based on storage location (GSC Ottawa, Dalhousie, Tunney's Pasture) and pail number. Samples that have been distributed to other researchers can also be identified here. (A suite of samples from the Isachsen Formation has been bequeathed to a Ph.D. project at Carleton University by C. Kingsbury).
Cuttings & Powders	Result of Inventory	The collection includes cuttings (crush) and powders of a number of samples. Powder inventory is particularly useful since available powders significantly cut pre-analysis sample preparation time. Samples with available cuttings and powders are identified with a tick mark in the appropriate column.
Whole Rock Geochemistry	W	Whole Rock (if available, identified with tick mark)
	EB	Whole Rock (if available, identified with tick mark)
	W	REE (if available, identified with tick mark)
	W	Rb-Sr (if available, identified with tick mark)
	W	Sm-Nd (if available, identified with tick mark)
	EB	Au and PGEs (if available, identified with tick mark)
Thin Section Available	Result of Inventory	If available, identified with tick mark
Mircoprobe work	W	Plagioclase, Pyroxene, Olivine and Opaques in individual columns; if available, identified with a tick mark
Age Dating	A	Mineral and whole rock Ar-Ar, if available identified with tick mark
	VW	Whole rock Ar-Ar, if available identified with tick mark

Hand Sample Photo	Preliminary inventory during Summer 2014; Further photos of samples analysed for geochem by BMS (Dec 2014-Feb 2015)	If available, identified with tick mark
Thin Section Photo	Preliminary inventory during Summer 2014	If available, identified with tick mark

Table 1: Information Available in the Database Describing the 1983-85 Legacy Collection. Sources of data: W: Williamson, 1988; EB: Ernst and Buchan, 2010; A: Avison, 1987; VW: Villeneuve and Williamson, 2006

	Field Season	Rock Type	Formation or Intrusion type	Le Reported in Field Notes
Axel Heiberg Island				
Strand/Expedition Fiord				
Twisted Ridge	'83	extrusive	Strand Fiord, Hassel	18
Bastion Ridge	'83	extrusive	Strand Fiord	27
Split Mountain	'83	extrusive	Strand Fiord	11
W Castle Mountain	'83	extrusive	Strand Fiord	7
Camp Ridge	'83	extrusive	Strand Fiord	5
Muskox Ridge SE	'83	extrusive	Strand Fiord	11
East Glacier Fiord Syncline	'83	extrusive	Strand Fiord	11
West Glacier Fiord Syncline	'83	extrusive	Strand Fiord	10
Expedition Ridge	'83	extrusive	Strand Fiord	6
Amarok River	'83	extrusive	Strand Fiord	6
Index Ridge	'83	extrusive	Strand Fiord	9
Erratics Island	'83	extrusive	Strand Fiord	7
Monkhead Mtn	'83	*intrusive*	*dykes, sills*	2
Bunde Fiord				
Celluloid Creek	'83	extrusive	Strand Fiord	18
Bjarnason Isl.	'83	extrusive	Isachsen	5
Arthaber Creek	'85	extrusive	Strand Fiord	24
Camp Five Creek	'85	extrusive	Isachsen	9
Scree Ridge	'85	extrusive	Isachsen	7
Cliff Section	'85	extrusive	Isachsen	4
Blackwelder	'85	extrusive	Isachsen	5
Lightfoot River				
Lightfoot River East	'85	*intrusive*	*dykes, sills*	28
Lightfoot River West	'85	*intrusive*	*dykes*	20
Buchanan Lake				
Buchanan Lake Intrusives	'85	*intrusive*	*dykes, sills*	44
Mokka Fiord	'84	extrusive	Isachsen (?)	4
Geodetic Hills				
Geodetic Hills	'85	extrusive	Isachsen	12
Ellesmere Island				
Eureka				
Blacktop Ridge	'85	*intrusive*	*sills*	7
Centreville Diabase	'84	*intrusive*		1

Blue Mountains (Hare Fiord)				
Blue Ridge	'84	ext, *int*	Isachsen, *dykes, sills*	14
Blackwelder Ridge	'84	ext, *int*	Isachsen, *dykes, sills*	14
Tanquary Fiord				
Rollrock River	'84	*intrusive*	*sills*	25
MacDonald River	'84	*intrusive*	*sills*	11
Lake Hazen/Piper Pass				
PP - Arctic Hare Mesa	'84	extrusive	Hassel	14
PP - Mount Doom	'84	*intrusive*	*sills*	6
PP - Dark Crystal	'84	*intrusive*	*sills*	14
PP - Elrond Ridge	'84	*intrusive*	*sills*	12
PP - Star Intrusive	'84	*intrusive*	*dykes, sills*	18
PP - Camp Sill	'84	*intrusive*	*sills*	7
Piper Pass River	'84	*intrusive*	*sills, dykes*	10
LH - Tropical Ridge	'84	extrusive	Hassel	10
LH - Mesa South	'84	extrusive	Hassel	6
LH - W Cuesta Creek	'84	*intrusive*	*sills, dykes*	14

Table 2: Summary of Localities and Available Samples in the 1983-85 Legacy Collection.
The rationale for projected new analyses is discussed in the text.

NOTES:

$ Complete Section of Lavas to be Analysed for GEM 2

* Analyses of Selected Samples from this Locality for GEM 2

\+ Previously analysed for geochemistry by Williamson (1988)

~ Not previously analysed for geochemistry by Williamson (1988)

C Samples bequeathed to C. Kingsbury for complementary Ph.D. thesis (Carleton University)

L Geochemistry available on samples from MCW 2008 field season

E HALIP Rocks of the Piper Pass/Lake Hazen area was recently studied in detail by Estrada (2014)

Field Area	Formations, *Intrusions*	Samples/Data available
Axel Heiberg Island		
Bals/Li Fiords	*dykes+sills*, Isachsen	Bals Fiord section available in Dalhousie Collection (Saumur et al., this volume)
Middle Fiord North	Isachsen, *dykes+sills*, possible Strand F.	Site of 2015 fieldwork (Williamson et al., this volume)
Agate Fiord North	Strand Fiord (thickest flow package), *possible dykes*	
Cape Levvel	Strand Fiord (thin volcanic package)	
Duck Bay Southeast	Strand Fiord	
Surprise Fiord West	*Surprise Fiord dyke swarm*	Site of 2015 fieldwork (Williamson et al., this volume)

Whitsunday Bay	*dykes*	
Schei Peninsula/White Mtn.	*dykes*	
Nunataks - Swiss & Princess Margaret Ranges	possible Strand Fiord, Isachsen, *dykes, sills*	
Ellesmere Island		
Emma Fiord/Audhild Bay	volcanics, *dykes*	Samples available in Dalhousie Collection; Saumur et al. this volume
NW Ellesmere (e.g., Phillips Inlet, Yelverton Bay, Hansen Pt.)	Hassel, *dykes, sills, pluton (e.g., Wootton Intrusion)*	Some Samples available in Dalhousie Collection (Saumur et al., this volume); Portions of field area studied by Estrada et al. (2006) and Estrada and Hinges-Kunst (2013).
Raanes Peninsula	*dykes*	Topic of B.Sc. Thesis (Hachkowski, 2011)
Other Islands		
Amund Ringnes Island N.	volcanics, *dykes*	
Ellef Ringnes Island	*saucer-shaped sills*	Evenchick et al., 2015 - some samples made available for geochemistry for GEM 2 HALIP

Table 3: Summary of selected localities that are not represented in the 1983-85 Legacy Collection.

HALIP LEGACY SAMPLES, PART II – THE DALHOUSIE UNIVERSITY COLLECTION

B.M. Saumur[1], M.-C. Williamson[1], A.L. Muecke[2] and G.K. Muecke[2]

[1.] Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario
[2.] 12 Apollo Court, Halifax, Nova Scotia

Saumur (this volume) described the rationale for the analysis of legacy sample collections and implications for these collections for Arctic fieldwork in summer 2015 under GEM 2 HALIP. That paper focused on the Ottawa Collection, one of the two legacy sample collections available to the GSC. The other collection, the Dalhousie Collection, stored in the Department of Earth Sciences at Dalhousie University (Halifax), is the focus of this paper.

Samples from the Dalhousie Collection were collected between 1984 and 1992 during fieldwork led by Dr. G. Muecke. This fieldwork, summarised in Table 1 below, was conducted at various localities on Axel Heiberg Island, Ellesmere Island and surrounding minor islands. Although several aspects of the geology of the Sverdrup Basin were studied, mapping and sampling of basalts, sills and dykes of the HALIP remained a prime focus for fieldwork. We note that several localities of NW Ellesmere, visited between 1986 and 1992, are not represented in the Ottawa collection (Saumur, this volume). These include Phillips Inlet, Emma Fiord, Hare Fiord, Kleybolte Peninsula, Krueger Island and Yelverton Inlet. Also of note are potential samples available from Bals Fiord, Axel Heiberg Island. These represent potential sites for future expeditions under GEM 2, and the availability of relevant samples from these areas will assist in constraining this work.

The compilation of legacy data and field notes for the Dalhousie collection has been contracted to A. Muecke and is currently ongoing. The completion and transfer of data, field notes and samples to the GSC is projected for the fall of 2015.

Table 1: Summary of field work in the Sverdrup Basin led by Dr. Gunter Muecke, Dalhousie University 1984 – 1992

REFERENCES

Cameron, B., 1989, Petrochemistry and Origin of Altered Permian Basalts in the Sverdrup Basin, Arctic Canada, MsC Thesis, Dalhousie University.

Henry, A.S., 1991, The Petrochemistry and Origin of the Bourne Complex, Northwestern Ellesmere Island, Canada, BSc Thesis, Dalhousie University,

Hinds, S.J., 1991,The Correlation and 40AR/39AR Age Dating of the Early Cretaceous Walker island Member Basalts Axel Heiberg Island – Canadian Arctic, BSC Thesis, Dalhousie University.

Jollimore, W., 1986. Analyses of Dyke Swarms within the Sverdrup Basin Queen Elizabeth Islands. BSc Thesis, Dalhousie University

MacRae, R.A., 1989, Palynology and Stratigraphy of an Upper Cretaceous Sedimentary Volcanic Sequence, Emma Fiord, Northwest Ellesmere Island, N.W.T., Canada, BSc Thesis, Dalhousie University.

MacRae, R.A., 1992, Palynology of the Bastion Ridge and Strand Fiord Formations Western Axel Heiberg island, Canadian Arctic Islands, NWT, MSc Thesis, University of Calgary.

Parsons, M.B., 1994, Geochemistry and Petrogenesis of Late Cretaceous Bentonites from the Kanguk Formation, Axel Heiberg and Ellesmere Islands, Canadian High Arctic, BSc Thesis, Dalhousie University.

Ritcey, D.H, 1989. A Geochemical Study of the Carboniferous Audhild Volcanics, Northwestern Ellesmere Island, Arctic Canada: Initial Volcanism in the Sverdrup Basin BSc Thesis, Dalhousie University.

Saumur, B.-M., 2015, HALIP Legacy Samples, Part I – The Ottawa Collection, *in* Dewing, K. (ed.) Report of activities for High Arctic Large Igneous Province (HALIP) - GEM 2 Western Arctic Region Project; Geological Survey of Canada Open File 7976, p. 9-14

Williamson, M.-C., 1988, The Cretaceous Igneous Province of the Sverdrup Basin, Canadian Arctic: field relations and petrochemical studies. Ph.D. thesis, Dalhousie University, Halifax, Canada.

Table 1 - Summary of Field Work in the Sverdrup Basin
Led by Dr. Gunter Muecke, Dalhousie University 1984 – 1992

Year	Party members	Field study localities	Research Objectives
1984	Gunter Muecke Marie-Claude Williamson	Ellesmere Island • Turnabout Glacier • Lake Hazen • Expedition Fiord • Tanquary Fiord	• Strand Fiord Formation, flows, dykes and sills (Williamson, 1988)
1985	Gunter Muecke Marie-Claude Williamson	Axel Heiberg Island • Buchanan Lake • Bunde Fiord	• Upper Isachsen Formation; flows, dykes and sills (Jollimore, 1986)
1986	Gunter Muecke Anne Muecke Barry Cameron Jennifer Bates	Ellesmere Island • Emma Fiord/Audhild Peninsula (south side) • Audhild Peninsula (north side) • Phillips Inlet (east) • Phillips Inlet (west) • Head of Hare Fiord	• Preliminary investigation of the bimodal (Esayoo) cretaceous volcanics and interbedded pyroclastics in the 'Audhild peninsula' between Audhild Bay and Emma Fiord (Ritcey, 1989; MacRae, 1989) • Mapping and sampling of the primitive basalt sequence of Phillips East and the bimodal sequence of Phillips West. • Measurement and sampling of dykes and sills cutting the Nansen Formation • Preliminary work on the Permian Esayoo Formation alkaline volcanics (Cameron, 1989)
1987 1987 (ctd.)	Gunter Muecke R. Andrew MacRae Doug Merritt, Jennifer Bates	Ellesmere Island • Emma Fiord/Audhild Peninsula (south side) • Audhild Peninsula (north side) • Feldholmen Island • Kleybolte Peninsula • Phillips Inlet (east) • Phillips Inlet (west) • Tongue Glacier (west)	• Continued investigation and mapping of the Audhild peninsula sequence initiated in 1986 • Preliminary examination of Bourne Complex volcanics and intrusive igneous rocks (Henry, 1991) • Continued examination of the Hansen Point Formation volcanics • Continued work on the Permian Esayoo Formation volcanics
1989	Gunter Muecke Andrew Henry David Ritcey	Ellesmere Island • Kreuger Island • Yelverton Inlet	• Continuation of work on the Bourne Complex volcanics and intrusive igneous • Continuation of work on the Hansen Point Formation volcanics -
1990	Gunter Muecke R. Andrew MacRae Graham Fisher	Axel Heiberg Island • Kanguk River • Hidden Icefield • Twin Diapirs • East Fiord • Camp Five Creek	• Upper Isachsen Formation volcanics (Hinds, 1991) • Strand Formation and Kanguk Formations volcanic sequence (MacRae, 1992; Parsons, 1994)

		• Celluloid Creek	• Invasive flows of East Fiord
1992	Gunter Muecke Eric Pearson Michael Parsons	Ellesmere Island • Fosheim Peninsular • Celluloid Creek • Bals Fiord • Bjarnason Island	• Sequence of sedimentary volcanics exposed in the Fosheim Anticline • Strand Formation volcanic sequence • Hassel Formation sedimentary sequence

REGIONAL STUDY OF HALIP SILL GEOCHEMISTRY AND ECONOMIC POTENTIAL

J. H. Bédard[1]

[1.] GSC-Québec, 490 De la Couronne, Québec, Québec (email: Jean.Bédard@Canada.ca)

INTRODUCTION

A 3 week field season on Axel Heiberg & Ellesmere islands was undertaken in the summer of 2015 in the framework of the GEM2 Western Arctic Project. There are three principal objectives of the activity.

1) Regional scale sill geochemistry, S-isotope geochemistry, exploration potential and petrogenesis.
2) Geochemistry, petrography and gas geochemistry a gypsum-hosted sill.
3) Geochemistry, petrography and gas geochemistry of a shale-hosted sill.

REGIONAL SCALE SILL GEOCHEMISTRY, S-ISOTOPE GEOCHEMISTRY, EXPLORATION POTENTIAL AND PETROGENESIS.

The 1st-order objective of the project is to obtain a representative sample set of sills from the HALIP in this area. Prior to fieldwork, the remote predictive map prepared by C. Deblonde (GSC-Calgary) was combined with the locations of existing archival samples collated by B. Saumur & M.-C. Williamson, in order to locate target sample sites. The 1st 4-5 days in the field were spent sampling these previously unsampled sites. Where possible, 4 samples were taken from each site: A) host rock; B) chilled margins; C) sill centers; D) pegmatoidal segregations.

Contact metamorphosed host rocks may contain metamorphic phases like monazite or titanite amenable to geochronological studies by Bill Davis. Similarly, pegmatoidal segregations in sill cores may contain zircon or baddeleyite that could allow age dating. Chilled margins are useful because they represent liquid compositions and are most easily interpreted in terms of liquid line of descent and petrogenetic modeling. However, experience has shown that chills are often perturbed by interaction with wallrocks, either synchronous with emplacement, or because of fluid-mediated transfers afterwards. Consequently, S-isotopic analyses will be performed only on sill cores, distal from these boundary effects. Comparison of chills and sill cores will allow us to document the impact of these secondary effects on whole-rock chemistry.

The geochemical database will be used in 3 ways: A) petrogenesis, B) regional correlations, C) exploration potential. Standard whole-rock geochemical analysis for majors and traces will allow basic characterization of magma populations. The database will be broken down into natural populations, and compared to the geochemical volcano-stratigraphy of M.-C. Williamson & B. Saumur to be generated in a parallel study. Age dating (B.Davis) will be focused on representative examples of these different populations. Geochemical data will first be interpreted in terms of differentiation mechanisms, crustal contamination scenarios, and partial melting of the mantle. All samples will be crushed in agate shatterboxes so as to allow follow-up isotopic analysis if desired. Analysis of platinum group elements and sulfur isotopes will determine whether any of the magma populations show evidence of prior sulfide immiscibility (depleted chalcophile elements) or assimilation of evaporitic facies (high ^{34}S) that would provide constraints on their exploration potential for Ni-Cu-PGE.

GEOCHEMISTRY, PETROGRAPHY AND GAS GEOCHEMISTRY OF A GYPSUM-HOSTED SILL

It has been proposed that assimilation of gypsum evaporite is an important component in the development of Norils'k-type conduit Ni-PGE orebodies. The argument is that small amounts of such a contaminant could trigger sulfide melt immiscibility in Ni-rich primitive melts. On the other hand, if too much of such a contaminant is assimilated, it could prevent the formation of immiscible melts because this type of contaminant is dominated by SO_4 complexes that would oxidize the melt. Since S-solubility is linked to elemental speciation, it is thought that oxidized melts allow S to dissolve as sulfate, which would prevent the formation of immiscible sulfides. Consequently, it is important to understand how such a contaminant is ingested.

Magmatically induced degassing of sulfate represents a potential trigger for climate change and global glaciations (snowball Earth hypothesis). It is therefore important to better understand how such lithologies respond to magmatically-driven heating events.

These two themes will be addressed using a variety of approaches: field relationships, petrography and mineralogy, contact metamorphism, geochemistry, S-isotopes and experimental simulations.

A site was selected in an undisturbed section of the Otto Fiord evaporite where remote imagery suggested the possibility of HALIP sills intruded into gypsum from which a closely spaced sample set was to be collected. Samples will be characterized in the field, petrographically, and with the electron-probe to determine the impacts of magma emplacement on host rocks, and to determine whether there are characteristic reaction facies associated with assimilation. Geochemical characterization will constrain the scale of the contact metamorphic halo, determine whether host rocks have degassed S to any degree, and whether there is any impact of contact metamorphism on S-isotopic signatures.

Intra-sill geochemical variations will be examined to constrain the effects of wallrock assimilation. Specifically, does the addition of sulfate generate strongly contaminated boundary layers, does the contaminant mix homogeneously, or is contamination occurring preferentially at the upper or the lower contact? Do sulfate hosted sills have geochemical signatures that differ from the dominant HALIP population? Are there any specific elemental or isotopic fingerprints associated with assimilation of sulfate that can be identified in the broader HALIP dataset, which would indicate that some sill populations are more prospective?

An experimental study to be conducted by collaborators based at Uppsala University (V.Troll & F.Deegan) will experimentally reproduce the sulfate assimilation mechanisms. Samples of gypsum embedded in uncontaminated HALIP basalt will be raised to magmatic temperatures and quickly quenched to freeze in diffusional haloes around gypsum enclaves. Charges will be examined petrographically and analyzed. Important questions include whether or not unusual reaction facies form that would prevent or modulate wholesale incorporation of sulfate; and what are the spatial scales and time-scales of contaminant homogenization? Preliminary experiments on a Victoria Island sample set implies that a broad S-rich halo forms around gypsum xenoliths. Detailed examination of these charges may allow characterization of dissolution mechanisms (Fe-S complexing? Molecular or atomic dissolution of S or S-H species? Dissolution of SO_4 complexes?) and S-diffusion rates that would allow a better characterization of gypsum contamination mechanisms. In terms of Ni-PGE exploration potential, it may be that oxygen diffuses faster than S, which would have a negative impact on S-immiscibility since it would oxidize the melt and allow formation of soluble SO_4 complexes. Conversely, if much of the O is lost early through degassing of CO_2 or H_2O, then this would leave reduced S species that would preferentially dissolve as Fe-S complexes in the melt, thus enhancing the potential for the formation of immiscible sulfide melts.

GEOCHEMISTRY, PETROGRAPHY AND GAS GEOCHEMISTRY OF A SHALE-HOSTED SILL

Magmatic assimilation of C-S-rich black shale has been invoked as another potential PGE-Ni-S ore-forming process. Black shales are commonly S-rich, and would perhaps provide enough S to induce sulfide melt immiscibility. The strongly reducing geochemistry of such shales would minimize S-solubility and favour formation of immiscible sulfide melts. Consequently, it is important to understand how such a contaminant is ingested into a basalt and whether this triggers immiscibility.

Magmatically induced degassing of complex C-O-H-S species from black shale also represents a potential trigger for climate change and global extinctions. It is therefore important to better understand how such lithologies respond to magmatically-driven heating events, and to better characterize the volumes and types of gas species emitted due to magmatic heating.

A third important feature is the extent to which magmatic heating can facilitate or impair the oil and gas potential of a basin. In the Sverdrup Basin that is the host for much of the HALIP magmatism, much of the oil and gas potential has been linked to the mudstone of the Murray Harbour Formation, which many consider the source rock for this resource. The study to be undertaken will examine the impact of HALIP magmatism on the basin-wide hydrocarbon and gas potential.

These topics will be addressed using a variety of approaches: field relationships, petrography and mineralogy, contact metamorphism, geochemistry, forward thermal modeling, organic matter characterization, gas chromatography, S-Mo-isotopes and experimental simulations.

A site has been selected in the Murray Harbour Formation; where HALIP sills intrude it. A closely spaced sample set was collected to either side of several of these sills. Samples were collected from various places along a sill, to better constrain thermal impacts. It is predicted that the host rocks above these sills will have degassed and that gas escape may have self-channeled. Host rocks will be examined to see if there are detectable fossil gas 'plumes' that could be characterized. It is predicted that a given sample from the host shales will have experienced complex overprints. Above the sill, high-T gas species liberated by prograde metamorphism will overprint distal low-T domains that may have previously lost low-T gas species. Conversely, in shale located below a sill it is predicted that low-T gas species rising from the distal halo will overprint proximal rocks that have already released high-T gas species. Gas liberated from the shale located below the sill may have ponded beneath the sill; and may have exploited joints in the cooling intrusion. Contacts will be examined to seek evidence of these overprints and possible fluid ponding effects.

Samples from the host rocks will be examined petrographically and characterized mineralogically by C. Yakimchuck (U.Waterloo) to pin down the width of the thermal halo. Numerical forward thermal models of sill cooling and heat transfer and diffusion through wallrocks will be developed by P.Nabelek (U.Missouri). These will validate the contact metamorphic temperatures and provide insights into the distances and lengths of time that host shales spend at high temperatures. These data will feed into the modeling for the oil & gas potential of the basin. Samples will be examined in GSC-Calgary to characterize the degree of organic matter maturation. Samples will be run through standard oil / gas potential procedures (Rock-Eval pyrolysis) to characterize them.

Whole-rock major and trace element chemistry will be examined to constrain the impacts of the thermal overprint on elemental abundances in distal vs proximal shales. Shale samples will be analyzed for S isotopes by B.Wing (U.McGill) so as to document the nature (if any) of degassing on S isotope species. B. Kendall (U.Waterloo) will examine the Mo isotope signatures to verify whether or not Mo isotope signatures are affected by contact metamorphism.

Intra-sill geochemical variations will be examined to constrain the effects of wallrock assimilation empirically. Is the sill signature best reproduced by bulk assimilation of shale, or do such sills only assimilate previously degassed contact-metamorphosed facies? Does the addition of shale generate strongly contaminated boundary layers, does the contaminant mix homogeneously, or is contamination occurring preferentially at the upper or the lower contact? Will this shale hosted sill have geochemical signatures that differ from the dominant HALIP population? Are there any specific elemental or isotopic fingerprints associated with assimilation of shale that can be identified in the broader HALIP dataset, which would indicate that some sill populations are more prospective?

An experimental study to be conducted by collaborators based at Uppsala University (V.Troll & F.Deegan) will experimentally reproduce shale assimilation mechanisms. Samples of shale embedded in uncontaminated HALIP basalt will be raised to magmatic temperatures and quickly quenched to freeze in diffusional haloes and reaction facies. Charges will be examined petrographically and analyzed. Important questions to be determined include whether or not unusual reaction facies form that would prevent or modulate wholesale incorporation of shale; what are the spatial scales and time-scales of contaminant homogenization; and does shale assimilation trigger small scale sulfide immiscibilty?

Samples of distal, undegassed shale will be heated experimentally and gas species measured by gas chromatography in Oslo by V.Troll and his collaborators. Residues of each heating increment will be set aside and shipped to Calgary to allow comparison between in-situ observations and experimentally 'matured' organic matter. Incremental heating will document the sequence, volumes and types of species emitted during thermal metamorphim of the Murray Harbour Formation. These gas species data will be interpreted in collaboration with Hamed Sanei of GSC-Galgary. The experimental data can then be compared to the natural example to deconvolute the contact metamorphic history, and to the results of the Rock-Eval procedure to determine if it accurately predicts hydrocarbon prospectivity. These data will also be combined with results of the thermal modeling to quantify the volumes and species of gas released by contact metamorphism on the basin scale. When combined with field and seismic survey data (M.Duchesne), these would provide rigorous constraints on palaeo-climatological impacts of the HALIP event. When input into modeling algorithms for oil and gas potential (N.Pinet), these data may allow a better estimation of how HALIP magmatism affects the oil and gas potential of the Sverdrup Basin. As such, this dataset will be used to validate the applicability of a generic oil and gas window to the Sverdrup Basin by directly measuring how heat affects the actual source rock for this basin.

REMOTE SENSING DATASETS FOR MAPPING OF HALIP ROCKS IN THE VICINITY OF EAST FIORD, WESTERN AXEL HEIBERG ISLAND

R.F. MacLeod[1], J.R. Harris[2], M.-C.Williamson[2], C. G. Kingsbury[3]
[1.] Geological Survey of Canada, 9860 West Saanich Road, Sidney, British Columbia
[2.] Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario
[3.] Department of Earth Sciences, Carleton University, 1125 Colonel By Dr., Ottawa, Ontario
(email: Roger.MacLeod@Canada.ca)

INTRODUCTION

Remote predictive mapping (RPM) is an approach that can enhance geological mapping programs by providing a basis for integrating and visualizing geological information. The power of the technique is the ability to work with complex and varied data sets such as satellite and aerial remote sensing, geophysical and geochemical surveys and available field mapping data. RPM is considered fundamental to the geological mapping process as it facilitates planning for field-based mapping campaigns and improves map products by providing a cost effective, aerial perspective of geologically complex terrains (Harris, 2008). The success of the RPM process, however, is dependant on the sources of the data used as well as the attributes of the geologic environment being investigated.

The objective of this summary paper is to discuss a preliminary RPM initiative we have carried out as part of the High Arctic Large Igneous Province (HALIP) project in the vicinity of East Fiord, Axel Heiberg Island, Nunavut. The remote sensing datasets that have been compiled are evaluated for their applicability for characterizing volcanic-intrusive complexes and their host sediments. As a reference for the assessment, we rely on the results of fieldwork conducted in this area during the 2013 summer season (Williamson et al., 2014).

REMOTE SENSING DATASETS

Remote sensing sensors collect imagery with varying spatial and temporal resolutions as well as spectral, radiometric, wavelength range, image fidelity, and swath width. Sensors that record the Very Near Infrared (VNIR), Short Wave Infrared (SWIR) and Thermal Infrared (TIR) portions of the electromagnetic (EM) spectrum are particularly useful for geologic mapping especially when the spatial resolutions match the intended scale of mapping. Previous studies have indicated that VNIR/SWIR/TIR portions of the EM spectrum help to improve the statistical accuracy of predictive maps (Behnia et al., 2012, Harris et al., 2014). In remote areas such as the Canadian High Arctic, satellite data are particularly useful as a source for producing first order maps owing to their unvegetated environment and the extensive archive of available imagery. As a result, moderate resolution multispectral satellite sensors that measure these wavelengths, mainly Landsat 7 & 8 and the Advanced Spaceborne Thermal Emission and Reflectance Radiometer, (ASTER), are widely used in RPM studies. SPOT-5 and -6 imagery, although lacking SWIR ad TIR wavelength information are also commonly collected to obtain imagery of large swath size at higher spatial resolution.

LANDSAT data

The Landsat 7 satellite sensor imagery collected for this region contains 4 VNIR wavelength bands, 2 SWIR bands, and 1 TIR band. All these bands are recorded at 30 m spatial resolution except for the TIR band which is recorded at 60 m. Landsat 8, compared to its precursor, has an increased radiometric resolution (12-bit compared to 8-bit), improved signal to noise ratio (SNR), and coastal blue and TIR bands. It however maintains the spatial resolution of 30 m in both the VNIR and SWIR bands.

Although the Landsat 8 sensor performance measures are improved over its predecessor they do not necessarily produce higher classification accuracies when attempting to produce predictive maps (Harris et al., 2014). The Landsat 8 imagery collected for this study contained relatively larger amounts of snow cover making the data less useful than the comparable Landsat 7 data.

ASTER data

The ASTER satellite sensor collects 14 bands: 3 VNIR wavelength bands with 15 m spatial resolution, 6 bands in the SWIR with a 30 m spatial resolution, and 5 bands in the TIR with 90 m spatial resolution. Unfortunately, the ASTER data that were previously acquired in the East Fiord area only contained visible wavelength bands. Attempts were made to obtain a scene with more spectral coverage, unfortunately other scenes found through online portals were either obscured by clouds or acquired in winter when the terrain is covered in snow and ice.

SPOT data

SPOT-6 data was specifically acquired during the Natural Resources Canada's Environmental Geoscience Program carried out from 2011-2014. SPOT-6 contains several characteristics that give it an advantage over the precursor SPOT satellites, including higher spatial resolution (6 m multispectral and 1.5 m panchromatic), thus providing the geologic detail necessary for fine-scale geological mapping. Although SPOT-5 also collects data at high resolutions (10 m for the multispectral bands and 5 m for the panchromatic bands), the data accessed through the Geobase web portal (www.geobase.ca) are resampled to a lower resolution (20 m and 10 m respectively).

In addition, the spectral wavelengths (bands) acquired by the new SPOT-6 sensor are different from those of SPOT-4 and 5. These precursor satellites measure the SWIR (1580-1750 nm), near infrared, red, and green wavelengths while SPOT-6 differs in that it gains the blue while losing SWIR wavelength information. SPOT-6 is therefore able to provide true colour composites. While there are some advantages in the VNIR portion, the SWIR data available from SPOT-5 has been shown to be particularly valuable for classification of geological units and can allow for the delineation of intrusive rocks (Behnia et al. 2012, Harris et al., 2014).

CASE STUDY IN THE ISACHSEN FORMATION

A priority for this RPM study was the assessment of the satellite data to identify and characterize igneous dykes and sills in the High Arctic Large Igneous Province (HALIP). Previous studies have suggested that igneous rocks are typified by lower reflectance in both the VNIR and SWIR wavelength (Harris et al., 2014; Behnia et al., 2012). Kingsbury (2015) noted that in near-true colour ASTER imagery, study area intrusions appeared darker grey and darker red than the surrounding sedimentary rocks and evaporate diapirs. It has additionally been noted that surrounding meter-scale gossanous rocks and/or true gossans known to be present in the area could be identified with high spatial resolution imagery containing blue wavelength information (Kingsbury, 2015). The use of a red over blue band ratio image is well known to help map rocks of higher iron oxide content. Thermal infrared (TIR) emissivity band(s) are also particularly useful for mapping igneous rocks, as the thermal radiation emitted from rocks is indicative of the silicate mineral content (Walter and Salisbury, 1989; Ninomiya, 2003 & 2004). Spectral indices of the ASTER thermal bands have successfully been used in studies to correlate index pixel values with SiO_2 weight percentage thus helping to either identify or delineate different igneous rock types (Ninomiya, 2004; Corrie et al., 2010), including on Axel Heiberg Island (Mosstajiri, 2013). Unfortunately, as we stated earlier, these bands are not available in the ASTER data previously collected for the East Fiord area. The Landsat 8 data collected for this study has two thermal bands, but the spatial and spectral resolution of the thermal bands is less than ASTER's and effective spectral indices for its bands have yet to be developed.

The RPM study in the East Fiord area of Axel Heiberg Island (Figure 1) focused on compiling and processing Landsat, SPOT and ASTER imagery as a basis for extending a regional mapping effort. Figure 2 shows panoramic photographs of a mapped volcanic-sedimentary succession believed to represent the Walker Island Member of the Isachsen Formation. The outcrop also includes a gossan at its base, the latter of which was described in detail by Percival et al. (2015). We used this well-exposed succession as a test area to evaluate the potential utility of the RPM methodology as an extension of planned mapping campaigns.

Figure 3 shows how the outcrop area is represented in colour composites of the SPOT 5 and 6 data. The photographs in Figure 2 were taken from the south east corner of this map image looking towards the northwest corner. The shadowed area in Figure 3 is running in this same direction emphasizes the downward sloping spur of the topography. Collected Landsat 7 & 8 and ASTER data are not shown as their spatial resolution was found to be insufficient to be of any use at this scale.

Although the landscape is displayed similarly for both SPOT-5 and SPOT-6 (see Fig. 3a, b, and c), the SPOT-6 imagery in (c) demonstrates the added benefit of the increased spatial resolution. Increased textural information is evident and assists in resolving the volcanic succession while the addition of the blue band helps with identifying the roughly 15 x 40 m gossan.

The shadowed upper right corner in each of the images of Figure 3 demonstrates the improvement in SNR and radiometric resolution of the SPOT-6 satellite. SPOT-6 is able to discern smaller changes in reflectance in the backslope of the hill as the radiometric resolution of the newer satellite is 12-bit (4096 levels of values) whereas the SPOT-5 satellite is 8-bit (256 levels of values). This increase helps to boost the range in levels of reflectance the sensor can record. Both the increase in levels and range of reflectance means that more subtle spectral features are visible. Radiometric resolution (or, more accurately, 'dynamic range') is particularly important for Arctic scenes as these typically contain large ranges in brightness levels, ranging from large highly reflective ice fields to dark oceans or rocks of low reflectance.

CONCLUSIONS

For the HALIP project, imagery from several earth observation sensors featuring a range of attributes has been acquired. From our review, the higher spatial resolution data, namely the SPOT-6 imagery, will be a crucial supplement to the sources of free, moderate resolution datasets (Landsat 7 & 8, ASTER, and SPOT-5) for providing fine scale first-order geologic information. Aerial photographs also provide this resolution, however SPOT-6 data covers a larger swath, is multispectral, contains significantly less shadows, and is geometrically more accurate. Interpretation of the shape, spectral signatures, texture, and topographic expressions present on the SPOT-6 data will allow for the delineation of small scale igneous rocks, possibly distinguishing them into their prospective types (i.e., flows, sills, dykes), and for identifying geological structures.

We currently lack data with key spectral coverage of the SWIR or TIR portions of the EM spectrum at spatial resolutions that are appropriate to the scale of mapping of HALIP goals. Such data exists using the WorldView-3 satellite sensor; however the expense of this data is prohibitive for this assessment.

REFERENCES

Behnia P., Harris J.R., Rainbird R.H., Williamson M.C. and Sheshparia, M., 2012. Remote Predictive Mapping of Bedrock Geology Using Image Classification of Landsat and SPOT Data, Western Minto Inlier, Victoria Island, Northwest Territories, Canada. International Journal of Remote Sensing, v. 33, no. 21, p. 6876-6903

Corrie, R., Ninomiya, Y., and Aitchison, J., 2010. Applying Advanced Spaceborne Thermal Emission And Reflection Radiometer (ASTER) Spectral Indices for Geological Mapping and Mineral Identification on the Tibetan Plateau. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Science, v. 38, Kyoto. p. 464-469.

Harris, J.R. (ed), 2008. Remote Predictive Mapping: An Aid for Northern Mapping; Geological Survey of Canada, Open File 5643, DVD.

Harris, J.R., He, J.X., Rainbird, R., and Behnia, P., 2014. A Comparison of Different Remotely Sensed Data for Classifying Bedrock Types in Canada's Arctic: Application of the Robust Classification Method and Random Forests. Geoscience Canada, v. 41, no. 4, p. 557-584.

Harrison, J.C., and Jackson, M.P.A., 2011. Bedrock geology, Strand Fiord-Expedition Fiord, western Axel Heiberg Island, northern Nunavut (parts of NTS 59E, F, G, and H); Geological Survey of Canada, Map 2157A, 2 sheets, scale 1:125 000.

Kingsbury, C.G., 2015. Remote predictive mapping of base metal gossans associated with evaporite diapirs and mafic intrusions in the South Fiord area, Axel Heiberg Island, Nunavut; *in* Environmental and Economic Significance of Gossans, (ed.) M.-C. Williamson; Geological Survey of Canada, Open File 7718, p. 14-22s.

Mosstajiri, T., 2013. Delineation of Igneous Rocks on Western Axel Heiberg Island Using Geopotential Data and Satellite Imagery. MSc thesis. University of Calgary, 146 pp.

Ninomiya, Y., 2003. Advanced Remote Lithologic Mapping in Ophiolite Zone with ASTER Multispectral Thermal Infrared Data. *In* Geoscience and Remote Sensing Symposium. International Geoscience and Remote Sensing Symposium (IGARSS'03). *In* Conference Proceedings. IEEE International. v. 3, p. 1561-1563.

Ninomiya, Y., 2004. Lithologic Mapping with Multispectral ASTER TIR and SWIR Data. *In* Remote Sensing, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, v. 5234, p. 180–190.

Percival, J.B., Williamson, M.-C., McNeil, R.J., and Harris, J.R. 2015. Morphology of gossans in the Canadian Arctic Islands, *in* Environmental and Economic Significance of Gossans, (ed.) M.-C. Williamson; Geological Survey of Canada, Open File 7718, p. 58-73.

Walter, L. S. and Salisbury, J. W., 1989. Spectral Characterization Of Igneous Rocks In The 8 - To 12 - Mm Region. Journal of Geophysical Research: Solid Earth, 94, p. 9203-9213.

Williamson, M.-C., Percival, J.B., Behnia, P., Harris, J.R., Peterson, R.C., Froome, J., Fenwick, L., Rainbird, R.H., Bédard, J.H., McNeil, R.J., Day, S.J., Kingsbury, C.G., Grunsky, E., McCurdy, M.W., Shepherd, J., Hillary, E.M., and Buller, G., 2014. Environmental and Economic Impact of Oxide-Sulphide Gossans, Northwest Territories and Nunavut; Geological Survey of Canada, Open File 7486, 10 p. and poster. doi:10.4095/293922

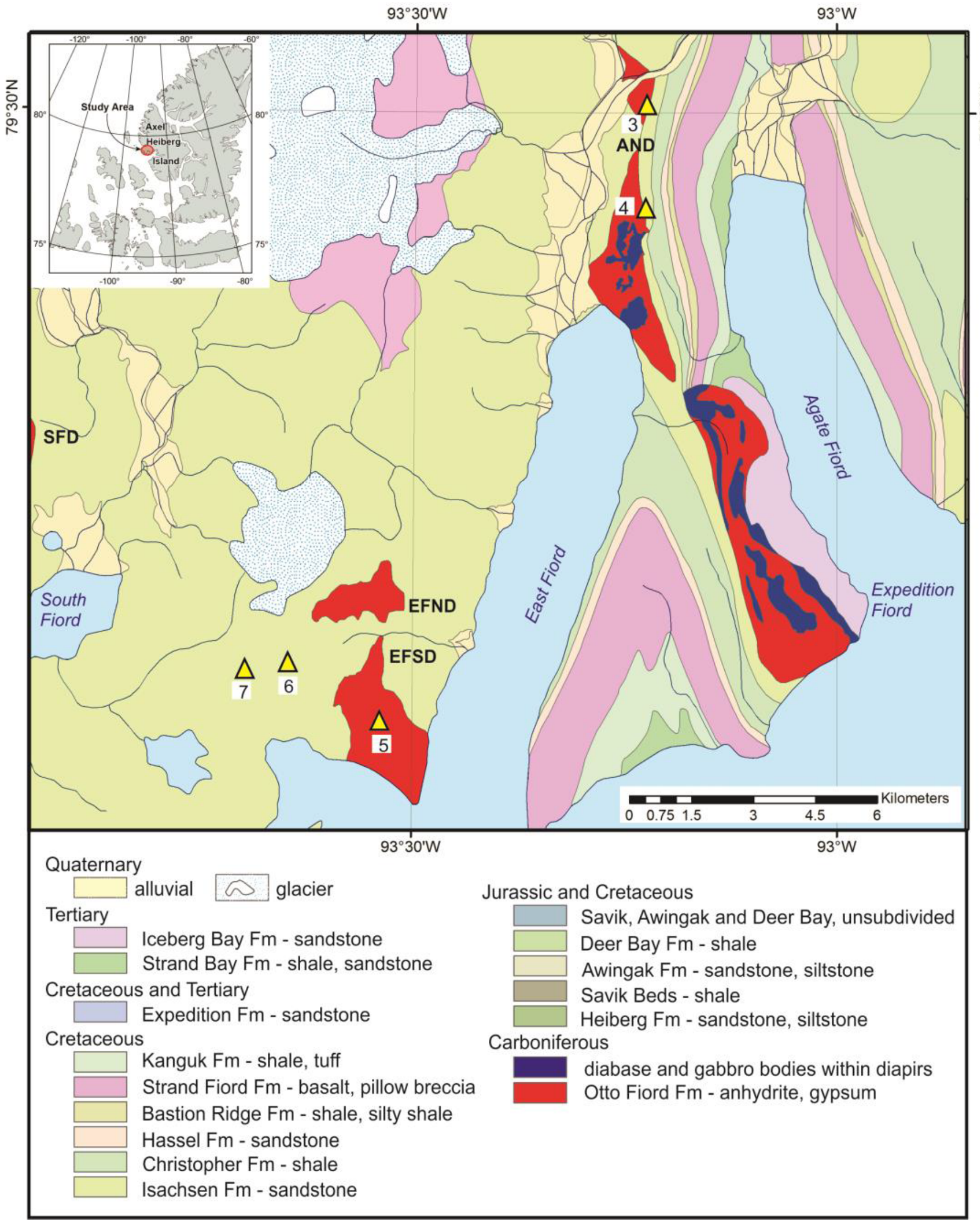

Figure 1. Simplified geological map of western Axel Heiberg Island, Nunavut, showing the location of the area where SPOT6 data are available and gossans shown as yellow triangles. The L7 gossan occurs on a ridge of volcanic rocks belonging to the Walker Island Member of the Isachsen Formation. Agate North Diapir (AND); East Fiord North Diapir (EFND); and East Fiord South Diapir (EFSD). Bedrock geology from Harrison and Jackson (2011). From Percival et al. (2015).

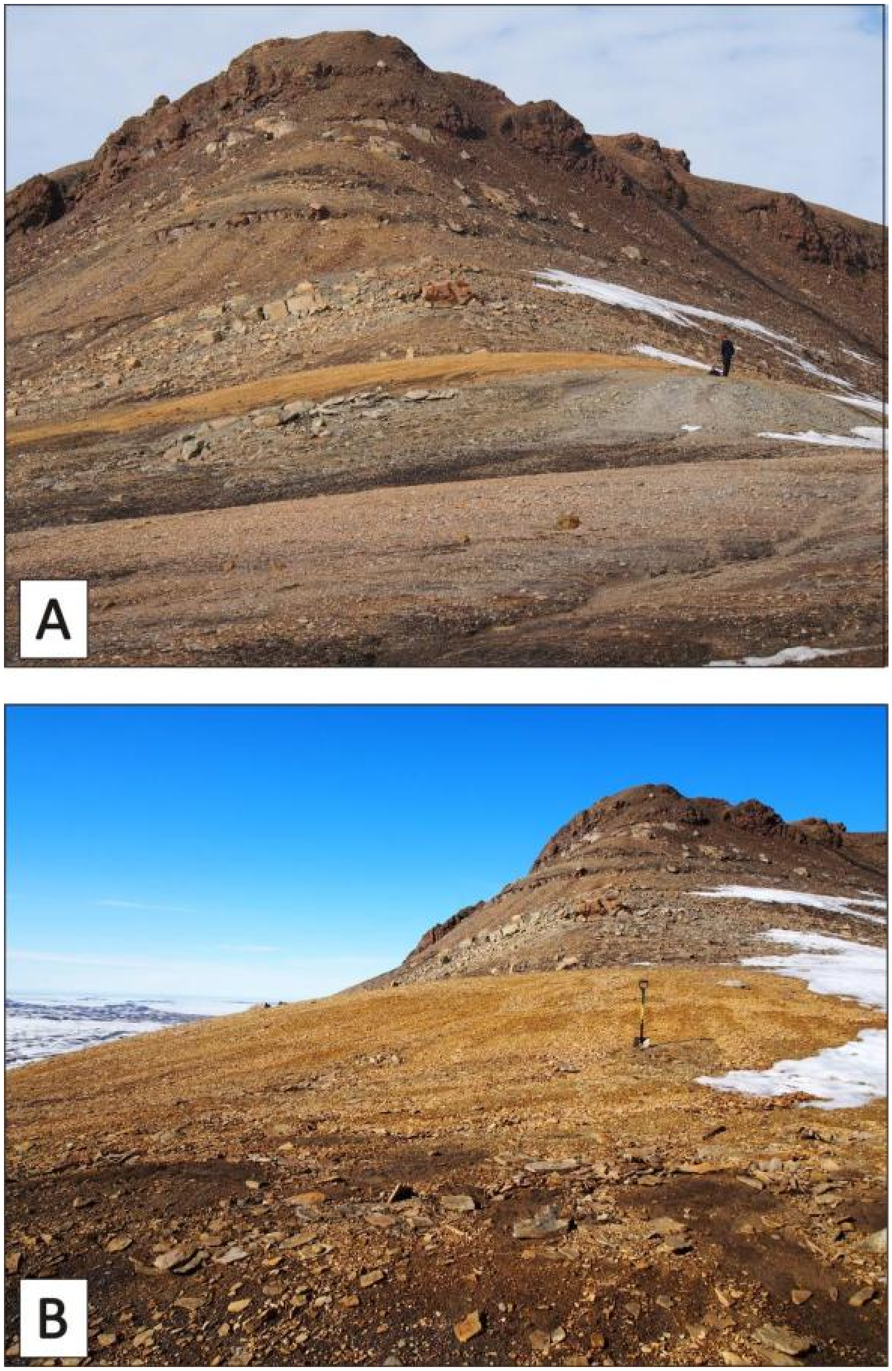

Figure 2. Panoramic view of the volcanic-sedimentary succession in the Isachsen Formation. (A) The succession is 60 m thick and consists of massive sandstone, shale beds and thin lava flows. (B) The gossan consists of thin, coherent and laterally continuous layers of alternating orange, yellow and grey sediments. From Williamson et al. (2014).

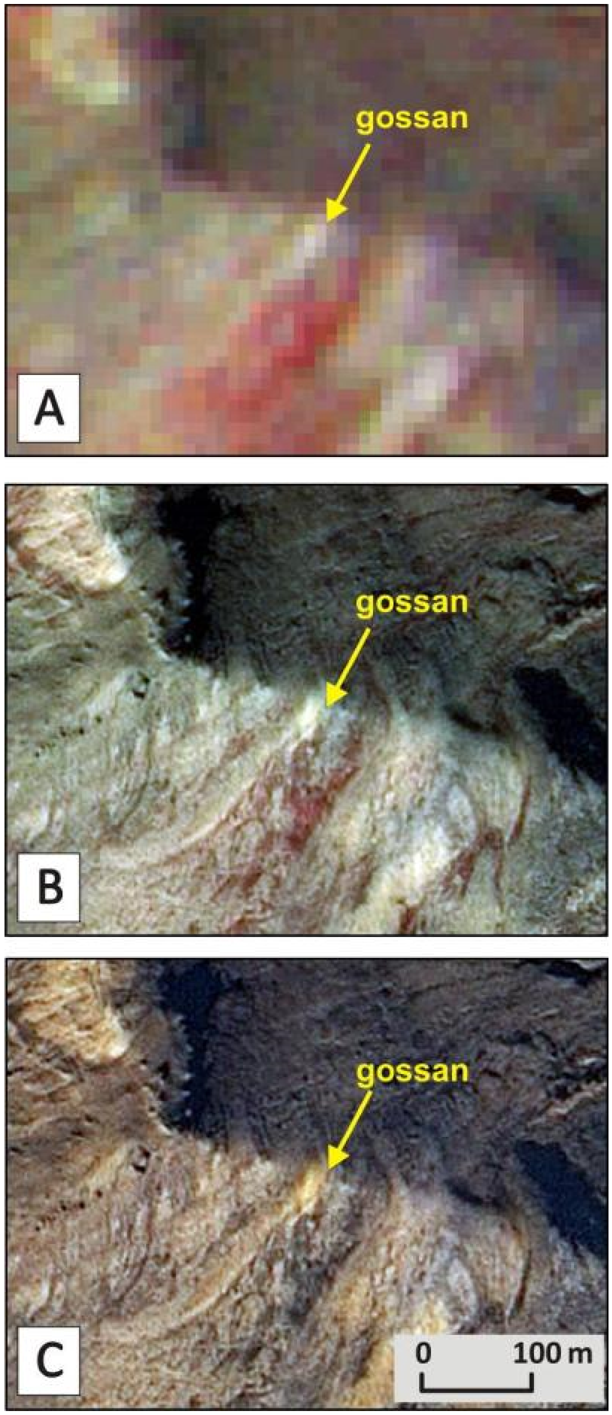

Figure 3. Pansharpened colour ternary images of (a) a false colour composite of a SPOT-5 of near infrared, red, and green wavelengths displayed by red, green, and blue channels respectively, (b) for comparison a false colour composite of these same wavelengths as recorded for the SPOT-6 sensor, and (c) a true-colour composite of SPOT-6. The location of the marked gossan is seen in figure 2. Both (b) and (c) show the improvement in higher SNR and radiometric and spatial resolution of the SPOT-6 satellite that allow for the subtle features to be visible in the upper right corner (backslope) of this area.

VOLCANIC-INTRUSIVE COMPLEXES OF WESTERN AXEL HEIBERG ISLAND

B.-M. Saumur[1], M.-C Williamson[1], and C.A. Evenchick[2]
[1.] Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario
[2.] Geological Survey of Canada, 1500-605 Robson Street, Vancouver, British Columbia,
(email: Benoit-Michel.Saumur@Canada.ca)

INTRODUCTION

Field work on Axel Heiberg Island, Nunavut, in July 2015 focused on three field areas (Fig. 1). This work will contribute towards enhancing the regional geochemical coverage of the HALIP. Mapping and sampling at each location will expand our current understanding of the mode of emplacement, geochemistry and prospectivity of the Canadian HALIP, and new work in these areas will contribute to our fundamental understanding of mafic volcanic-intrusive systems.

AGATE FIORD

The area, located ~40 km NW of the Strand-Expedition Fiord area, hosts what may be the thickest known succession of lava flows in the Strand Fiord Formation. For this reason, this locality may be located in proximity to one or more magmatic centre(s). The section will thus provide important observations on the three-dimensional geochemical variations and architecture of the magmatic system with implications for Ni-Cu-PGE prospectivity.

Sampling and sections measured will be compared and correlated to previous results for areas to the S and SE (cf., Williamson, 1988; Williamson and MacRae, 2001). The exposures of Strand Fiord Formation and Isachsen Formation in the East Fiord area Agate Fiord have the potential of generating a high-resolution eruptive history for both volcanic successions using U-Pb zircon geochronology obtained from coarse grained basaltic flows, volcaniclastic rocks or intraflow paleosols (after Schoene et al., 2014).

MIDDLE FIORD

This study area is located ~20 km WNW of Agate Fiord. Numerous sills and dykes that appear to crosscut the Isachsen Formation, and may represent part of the feeder system for the Strand Fiord Formation flood basalts. Intrusive magmatic Ni-Cu-PGE systems tend to form in conduits where flow can be focused to allow for the efficient mobilization, transport and deposition of dense magmatic sulphide (Saumur and Cruden, 2013; Barnes et al., in press). With this observation in mind, field work will focus on elucidating the geometry of the feeder system and how it may relate to the overall architecture of the Strand Fiord formation and the HALIP.

SURPRISE FIORD

The Surprise Fiord dyke swarm characteristically shows a very different orientation, roughly ESE-WSW, to that of N-S dykes of the Queen Elisabeth Dyke Swarm (Buchan and Ernst, 2006). Access to the area is difficult, and thus little is known of the age, geochemical or structural relationships between the Surprise Fiord dykes and other manifestations of the HALIP in the east-central Sverdrup Basin. The origin of ESE-WSW trending dykes along with their relationship with respect to other components of the HALP remain unclear, although Buchan and Ernst (2015) have tentatively proposed that they may represent part of a circumferential swarm generated at a hot spot and hence are co-eval with the N-S swarm.

Geological maps at a scale of 1:250,000 (Thorsteinsson, 1971) reveal complex field relationships between individual intrusions and local faults, rectilinear geometries and potential bifurcations. Fault-mediated mafic intrusive complexes represent ideal environments for pulsed magma interaction, which in turn would favour the enrichment of sulphides in Ni-Cu if sulphides are present (Bédard et al., 2012). Furthermore, field evidence from world class magmatic Ni-Cu-PGE deposits such as Voisey's Bay (Labrador) suggests that pre- to syn-emplacement wall rock structural controls can affect the geometry of intrusive systems which, in turn, can control the localization of mineralization (Saumur et al., 2015). One or more of these processes may have occurred may be observed within the Surprise Fiord Dyke swarm. This hypothesis will be tested through detailed mapping and geochemical/petrological sampling of the intrusive complex.

OTHER AREAS OF INTEREST

An exposure of massive sulphide, ~2 km E of Expedition Fiord (30 km SW of Agate Fiord North), was identified during field reconnaissance by Vale Inco in 2008 (Goddard, 2010). The occurrence is likely associated with the km-scale gabbroic Wolf intrusion and nearby dykes. New geochemical sampling and mapping of the massive sulphides will provide significant insight on the Ni-Cu-PGE prospectivity of the area.

A ~5 km scale concentration of Cretaceous dykes occurs on Stolz Peninsula, 1 km NE of Skaare Fiord (100 km NE of Surprise Fiord West) (Thorsteinsson, 1972b). The small complex contains both N-S and ESE-WSW oriented dykes. Similar to the Surprise Fiord West complex, it may represent a site of high magma flux.

REFERENCES

Barnes, S.J., Cruden, A.R., Arndt, N.T., and Saumur, B.-M., in press. The mineral system approach applied to magmatic Ni-Cu-PGE sulphide systems; Ore Geology Reviews.

Bédard, J.H., Naslund, H.R., Nabelek, P., Winpenny, A., Hryciuk, M., Macdonald, W., Hayes, B., Steigerwaldt, K., Hadlari, T., Rainbird, R., Dewing, K. and Girard, É., 2012. Fault-mediated melt ascent in a Neoproterozoic continental flood basalt province, the Franklin sills, Victoria Island, Canada; GSA Bulletin, v. 124, p. 723-736.

Buchan, K.L. and Ernst, R.E., 2006. Giant dyke swarms and the reconstruction of the Canadian Arctic islands, Greenland, Svalbard and Franz Josef Land; *In* (eds.) E. Hanski, S. Mertanen, T. Rämö, J. Vuollo, Dyke swarms—time markers of crustal evolution, Taylor & Francis, London, p. 27–48.

Buchan, K.L. and Ernst, R.E., 2015. A giant circumferential dyke swarm associated with the High Arctic Large Igneous Province (HALIP) – a possible analogue from coronae on Venus; Abstract # P42A-05, AGU-GAC-MAC-CGU Joint Assembly, 3-7 May 2015, Montréal, Canada.

Goddard, C., 2010. Report of Work Vale Inco Limited Axel Heiberg – Ground geochemical and geological survey (July 12 – August 2, 2008); Vale Inco Internal Report, 21 pp., 8 appendices.

Saumur, B.-M., Cruden, A.R., Evans-Lamswood, D.M., and Lightfoot, P.C., 2015. Wall rock structural controls on the genesis of the Voisey’s Bay intrusion and its Ni-Cu-Co magmatic sulfide mineralization (Labrador, Canada); Economic Geology, v. 110, p. 691-711.

Saumur, B.-M. and Cruden, A.R., 2013. Chonoliths, stocks, pipes, and aggregate plutons: the geometric complexity of intrusions that host mineral deposits; Geological Society of America Abstracts with Programs. v. 45, no. 7, p.227.

Schoene, B., Samperton, K.M., Eddy, M.P., Keller, G., Adatte, T., Bowring, S.A., Khadri, S.F.R., and Gertsch, B., 2014. U-Pb geochronology of the Deccan Traps and relation to the end-Cretaceous mass extinction, Science Express, 11 December 2014, Page 1, 10.1126/science.aaa0118.

Thorsteinsson, R., 1971. Geology, Middle Fiord, District of Franklin; Geological Survey of Canada, "A" Series Map 1299A, 1 sheet. doi:10.4095/109124

Thorsteinsson, R., 1972a. Geology, Glacier Fiord, District of Franklin; Geological Survey of Canada, "A" Series Map 1304A; 1 sheet. doi:10.4095/109127

Thorsteinsson, R, 1972b. Geology, Eureka Sound South, District of Franklin; Geological Survey of Canada, "A" Series Map 1300A; 1 sheet. doi:10.4095/123320

Williamson, M.-C., 1988. The Cretaceous Igneous Province of the Sverdrup Basin, Canadian Arctic: field relations and petrochemical studies; Ph.D. thesis (unpubl.), Dalhousie University, Halifax, Canada, 417 pp.

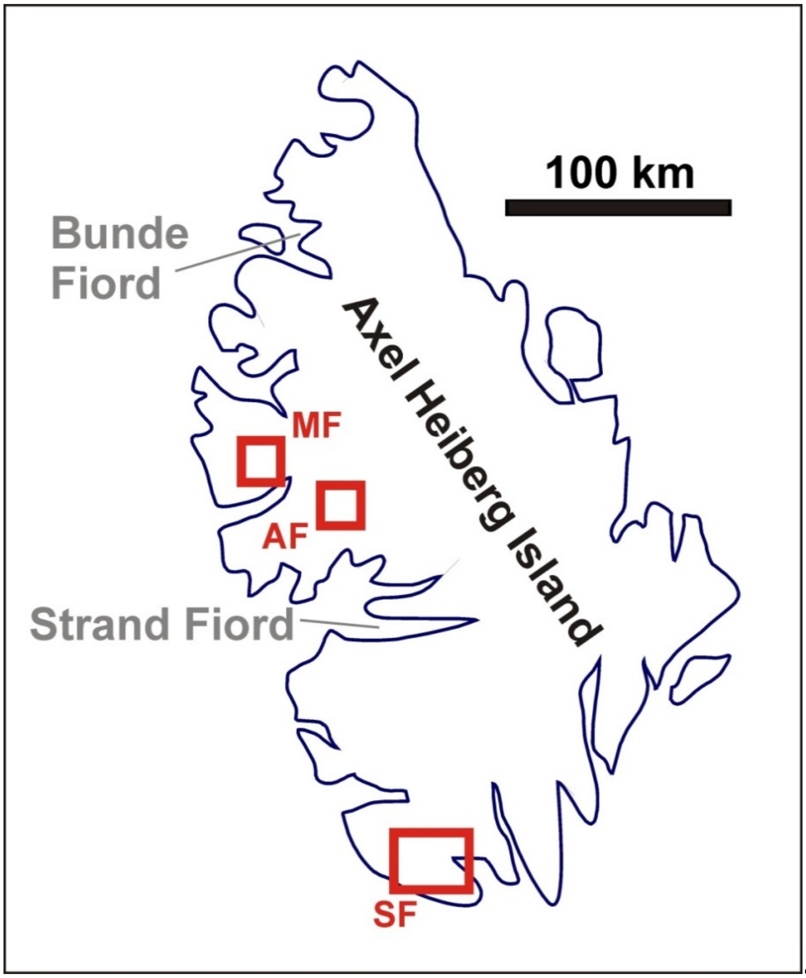

Figure 1: Field areas for 2015, Western Axel Heiberg Island. AF: Agate Fiord; MF: Middle Fiord; SF: Surprise Fiord Dyke swarm. Sizes of field areas are approximate.

DRAINAGE GEOCHEMISTRY AND INDICATOR MINERALS, AXEL HEIBERG ISLAND, NUNAVUT

R.J. McNeil
Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario
(email: Rick.McNeil@Canada.ca)

INTRODUCTION

As part of the High Arctic Large Igneous Province (HALIP) activity, Western Arctic Region Project, a stream sediment and water geochemistry survey was carried out in three areas of Axel Heiberg Island, Nunavut, to evaluate its economic mineral potential. In addition, bulk sediment samples werecollected for the recovery of indicator minerals from the heavy mineral contents at selected sites.

DRAINAGE SURVEY PROTOCOLS

Figure 1 illustrates the methodology applied to stream sediment and water surveys carried out by the Geological Survey of Canada. A set of three water samples, filtered-acidified (FA), unfiltered-acidified (UA) and filtered-unacidified (FU) are collected from the actively flowing part of the stream where the FA and FU are filtered on-site. The FA and UA are preserved by acidifying with nitric acid. Stream sediment samples of silt and/or fine grained clastic material from the stream channel are collected by hand from several points in the active channel while moving upstream, typically over a distance of 5 to 15 m. Bulk stream sediment samples are collected for their heavy mineral content from high-energy environments such as the head of active gravel bars. Roughly 12–15 kg of ≤ 2 mm stream sediment is wet-sieved on site.

PREVIOUS WORK

The GSC drainage survey protocol was applied in July 2013 to an area located in the vicinity of East Fiord on western Axel Heiberg Island (Figure 2). The study was the first systematic drainage survey carried out at this latitude following the National Geochemical Reconnaissance survey methodologies. The approach and results are described in McNeil et al. (2015). This area is host to a cluster of Tertiary diapirs cored by Otto Fiord Formation that intrude the Mesozoic sedimentary-volcanic succession (Harrison and Jackson, 2014). The innovation in this study consisted in comparing the geochemical signatures in mafic HALIP rocks (bedrock), gossans and stream sediments (Figure 3; Kingsbury et al., 2013). All the field stations were reached by way of foot traverses, without helicopter support. The samples from this study 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.

2015 SURVEY

The helicopter supported reconnaissance regional drainage survey was undertaken between July 27th and August 6th, 2015 in the central-eastern part of Axel Heiberg Island in three geologically distinct areas located between Whitsunday Bay and Lightfoot River. Drainages in these areas are optimal for a stream sediment and water survey. Drainages are easily accessible and the drainage system is very well defined. The stream sediment is optimal for silt and heavy mineral sampling. The glacial history of the area is such that the material found in drainages, appear to be locally derived and not transported by glaciers over a large distance. Therefore data generated from the collected samples should be a useful representation of the local geology. 75 sites were collected.

Lightfoot River

This area is characterized by a swarm of subparallel mafic dykes of HALIP age. The geochemical signature of the dykes has been investigated during previous studies (Jowitt et al., 2014). There are no evaporite diapirs present in the area.

Geodetic Hills

This area is characterized by the presence of thin lava flows in the Isachsen Formation, sills and dykes that will be mapped and sampled by the HALIP team. The stream sediment survey will enable an evaluation of this area away from the influence of evaporite diapirs.

Expedition Fiord

This area is characterized by the presence of widespread volcanic rocks (Strand Fiord Formation and Isachsen Formation), mafic sills and dykes. Rafts of mafic igneous rocks are commonly found within evaporite structures. Gossans are conspicuous and often occur at the periphery of salt domes (Williamson et al., 2011; Harrison and Jackson, 2014; Percival et al., 2015). The occurrence of massive sulphides reported by Goddard (2010) represents a significant discovery that will be taken into account in the survey plan.

Whitsunday Bay

This area shows many of the same stratigraphic features as the Expedition Fiord area with the following exceptions: (1) the Strand Fiord Formation and Isachsen Formation volcanic rocks are not present; (2) the Whitsunday Diapir does not show evidence of interaction with igneous rocks. This area could not be completed due to weather.

WORK SUMMARY

Two types of sampling sites were targeted during this study: (A) smaller first and second order streams in the upper reaches of the drainage for silt and water; and (B) larger third and fourth order streams for silt, water and bulk sediment for indicator minerals. More detailed sampling will be conducted in and around the diapirs to better evaluate their economic mineral potential, as results from the 2013 drainage study (McNeil et al., 2015) indicate the diapirs may play a significant role in focusing mineralization.

REFERENCES

Goddard, C., 2010. Report of Work Vale Inco Limited Axel Heiberg – Ground geochemical and geological survey (July 12 – August 2, 2008); Vale Inco Internal Report, 21 pp., 8 appendices.

Harrison, J.C., and Jackson, M.P.A., 2011. Bedrock geology, Strand Fiord-Expedition Fiord, western Axel Heiberg Island, northern Nunavut (parts of NTS 59E, F, G, and H); Geological Survey of Canada, Map 2157A, 2 sheets, scale 1:125 000.

Harrison, J.C., and Jackson, M.P.A., 2014. Tectonostratigraphy and allochthonous salt tectonics of Axel Heiberg Island, central Sverdrup Basin, Arctic Canada; Geological Survey of Canada, Bulletin 607, 124 pp

Jowitt, S.M., Williamson, M.-C., and Ernst, R.E., 2014. Geochemistry of the 130 to 80 Ma Canadian High Arctic Large Igneous Province (HALIP) event and implications for Ni-Cu-PGE prospectivity; Economic Geology, v. 109, no. 2, p. 281-307. doi:10.2113/econgeo.109.2.281

Kingsbury, C.G., Williamson, M.-C., Day, S.J.A., and McNeil, R.J., 2013. The 2013 Isachsen expedition to Axel Heiberg Island, Nunavut, Canada: A field report; Geological Survey of Canada, Open File 7539, 6 p. + poster. doi:10.4095/29384

McNeil, R.J., Day, S.J.A., and Williamson, M.-C., 2015. Stream sediment and water geochemical study, Axel Heiberg Island, Nunavut, Canada, *in* Environmental and Economic Significance of Gossans, (ed.) M.-C Williamson; Geological Survey of Canada, Open File 7718, p. 85-96.

Percival, J.B., Williamson, M.-C., McNeil, R.J., and Harris, J.R. 2015. Morphology of gossans in the Canadian Arctic Islands, *in* Environmental and Economic Significance of Gossans, (ed.) M.-C. Williamson; Geological Survey of Canada, Open File 7718, p. 58-73.

Williamson, M.-C., Smyth, H.R., Peterson, R.C., and Lavoie, D., 2011. Comparative geological studies of volcanic terrain on Mars: Examples from the Isachsen Formation, Axel Heiberg Island, Canadian High Arctic; Geological Society of America, Special Paper 483, p. 249-261.

Williamson, M.-C., Percival, J.B., Harris, J., Peterson, R.C., Froome, J., Bédard, J., McNeil, R.J., Day, S.J., Kingsbury, C.G., Grunsky, E., McCurdy, M., Shepherd, J., Hillary, B., and Buller, G., 2014. Environmental and economic impact of oxide-sulphide gossans, Northwest Territories and Nunavut; Geological Survey of Canada, Open File 7486, 10 p. + poster. doi:10.4095/293922

Williamson, M.-C., McNeil, R.J., Day, S.J.A., McCurdy, M.W., Rainbird, R.H., and Grunsky, E.C., 2015. Environmental impact of gossans revealed by orientation surveys for base metals in the Canadian Arctic Islands, *in* Environmental and Economic Significance of Gossans, (ed.) M.-C Williamson; Geological Survey of Canada, Open File 7718, p. 74-84.

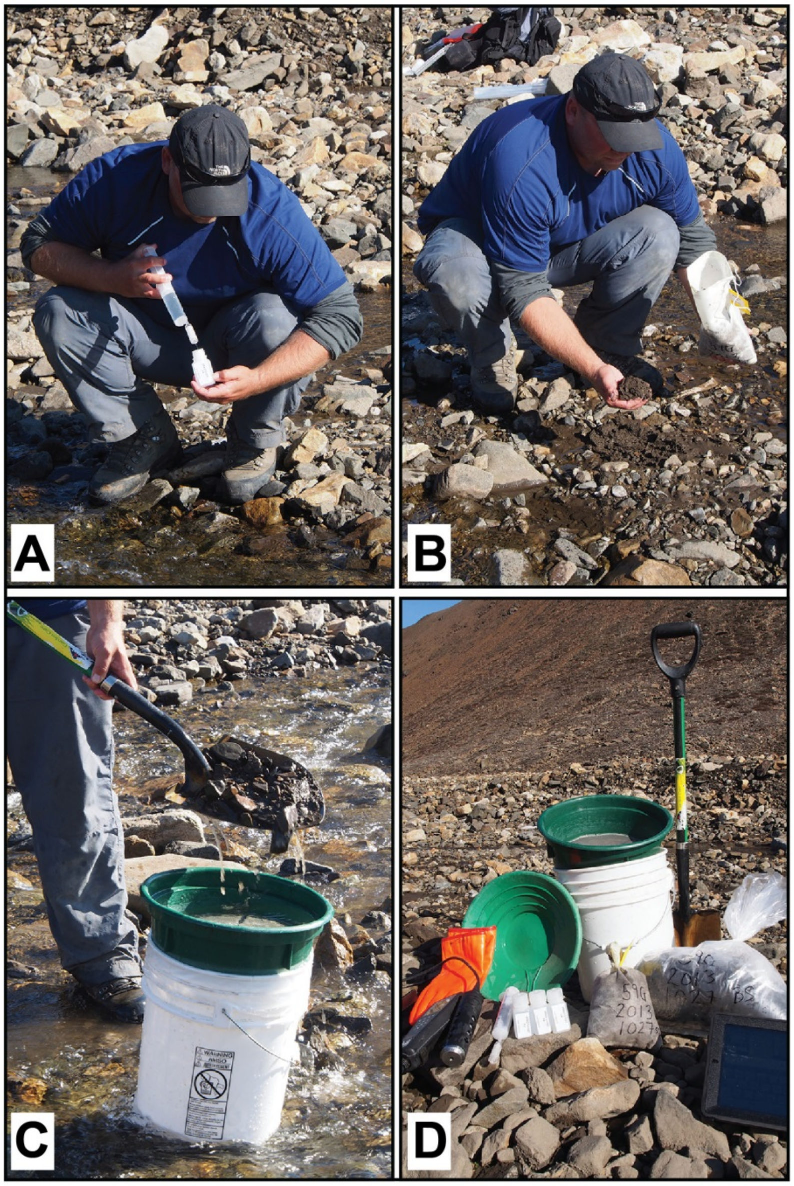

Figure 1. Sampling equipment and protocols: (A) Filtering water sample with 0.45 µm filter into 60ml HDPE bottle. (B) Approximately 2 kg of wet silt and clay is collected from lower energy part of streams into a spun-bonded polyester cloth bag. (C) Approximately 12-15 kg bulk sediment for heavy minerals is collected by wet-sieving with a 2 mm mesh sieve in higher energy part of streams into large plastic bags. (D) Field equipment used and samples collected at a typical stream site. From Williamson et al. (2014).

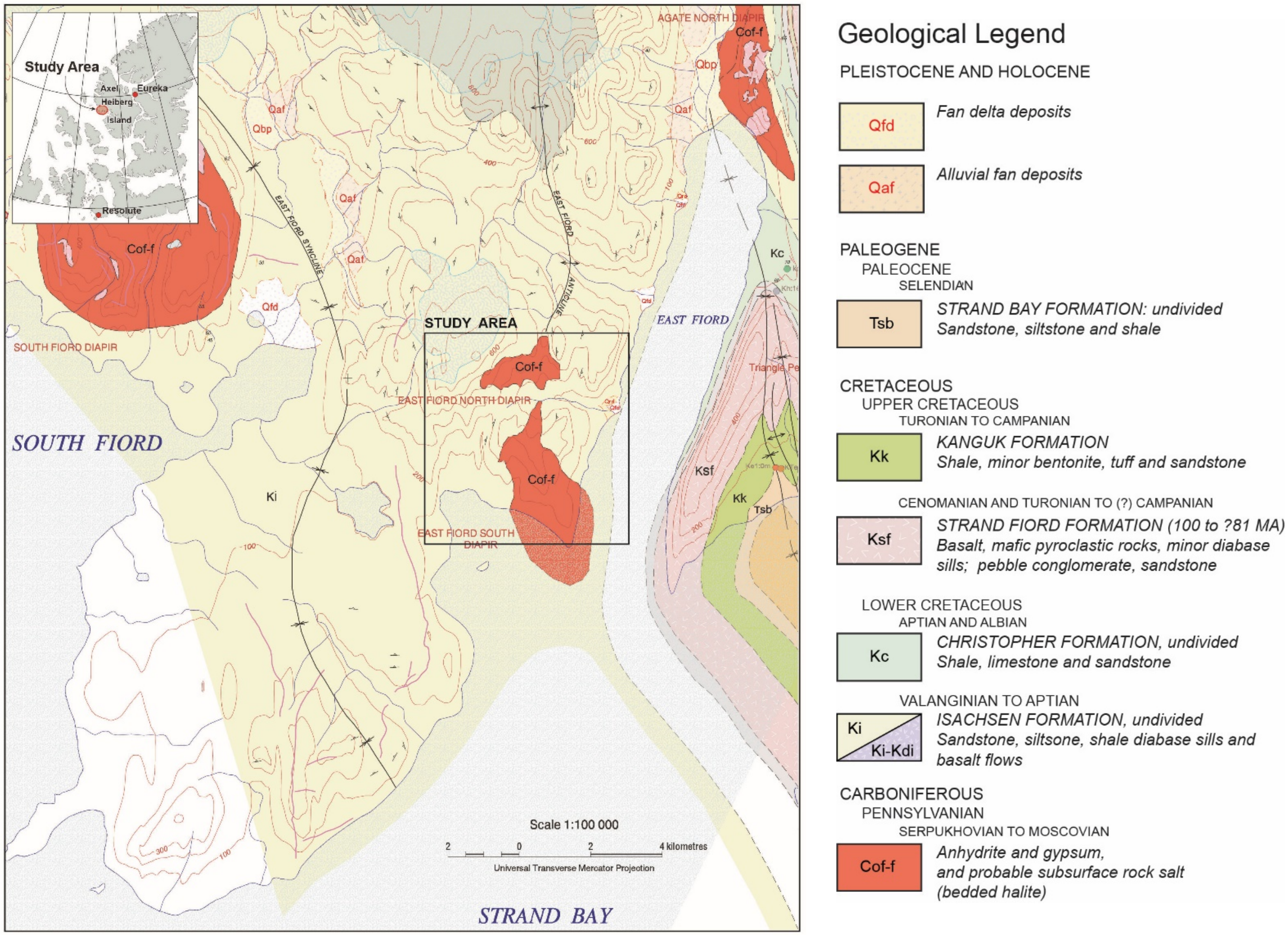

Figure2. Bedrock geology of the northwestern shore of Expedition Fiord area modified from Harrison and Jackson (2011). The map shows the probable offshore extension of lithological units in the eastern part of the study area, including salt domes. (From McNeil et al. 2015).

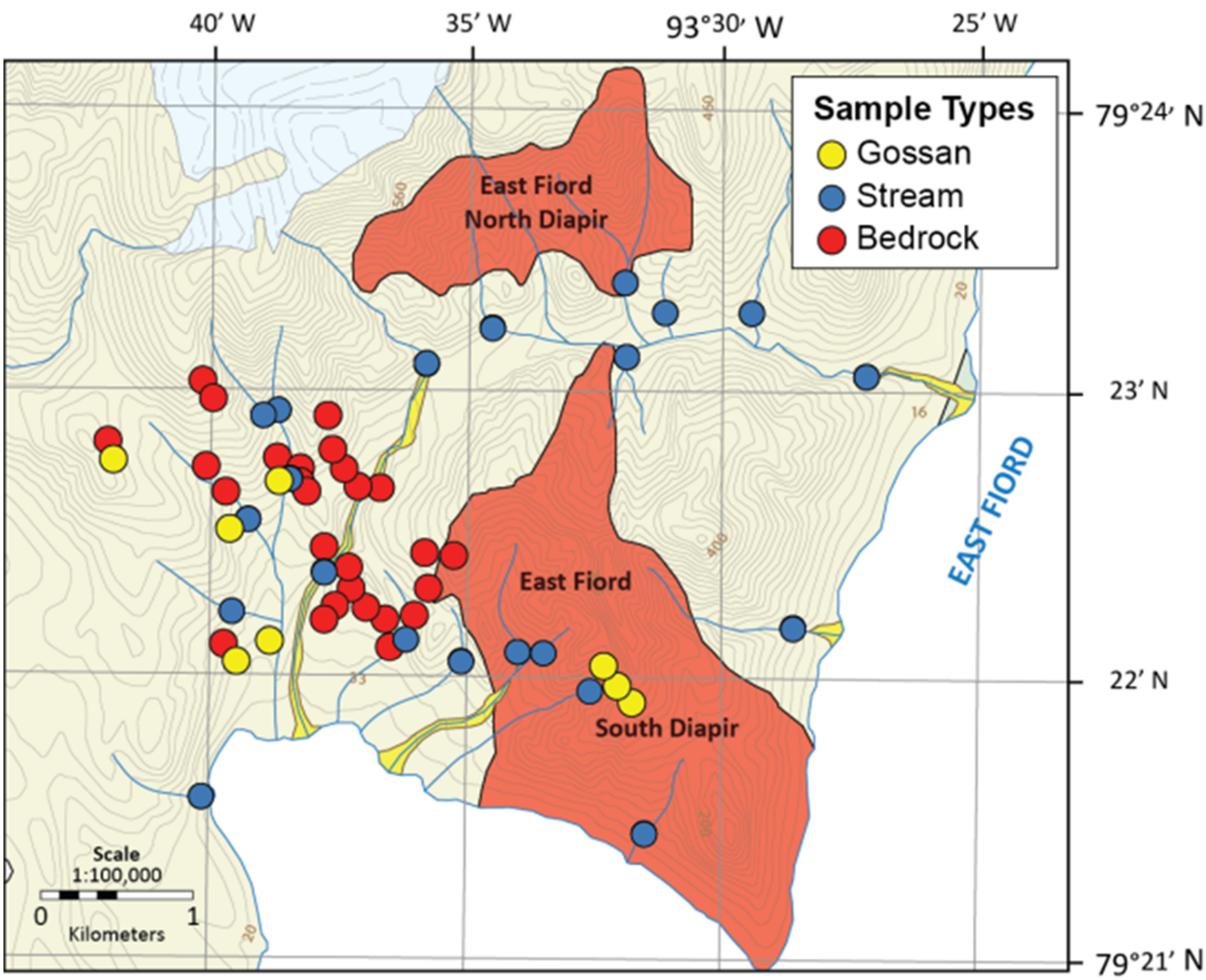

Figure 3. Map showing locations for gossan, streams and bedrock samples collected in summer 2013. (Modified from Williamson et al., 2015)

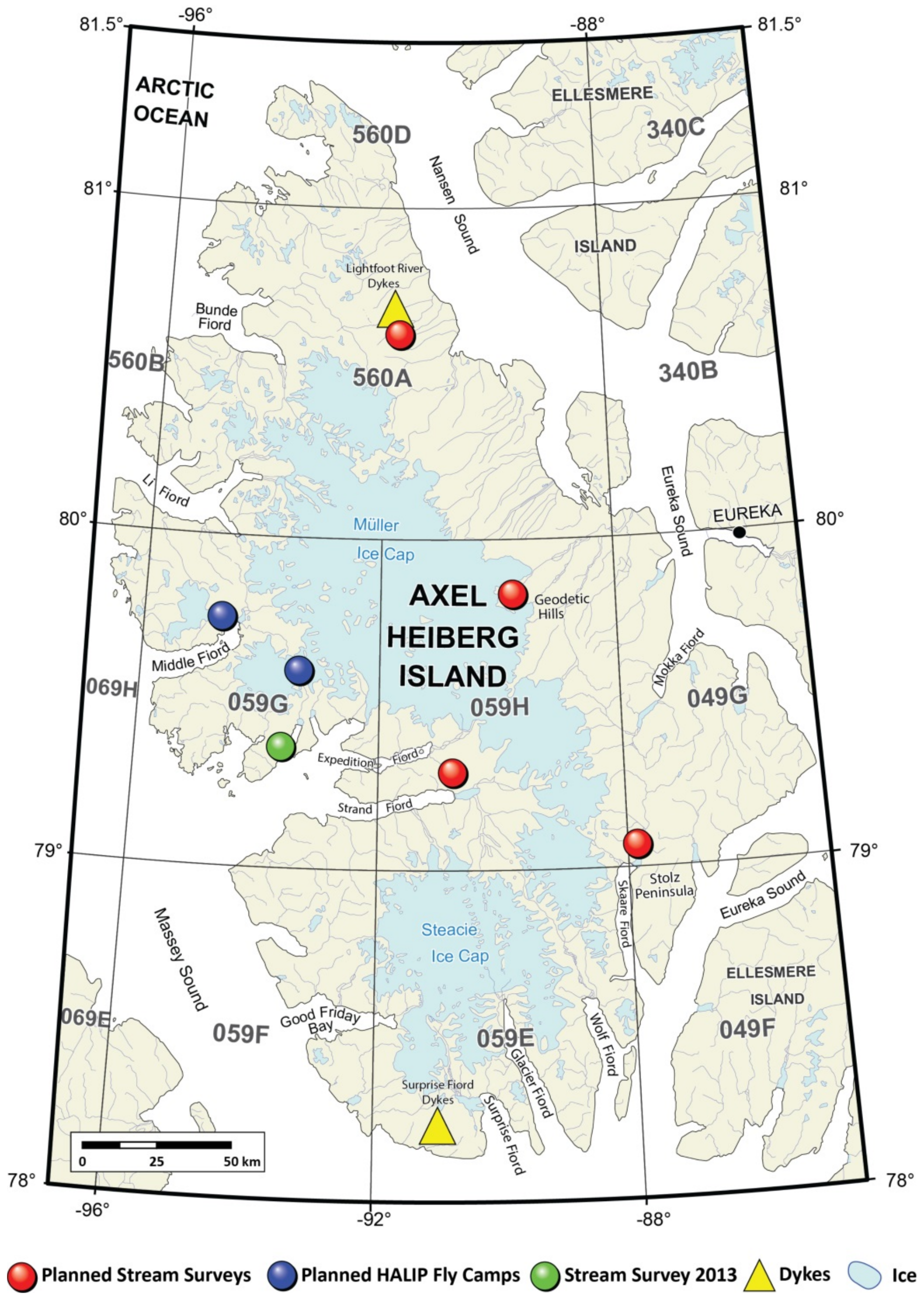

Figure 4. Map of Axel Heiberg Island showing the 2013 drainage study location in the East Fiord area (green), the 2015 drainage study areas (red) and the location of HALIP study areas focused on HALIP volcanic-intrusive complexes (blue).

INFLUENCE OF IGNEOUS INTRUSIONS ON THERMAL MATURITY OF ORGANIC MATTER IN THE SVERDRUP BASIN

K. Dewing[1], S.E. Grasby[1], H. Sanei[1], and F. Goodarzi[2]

[1.] Geological Survey of Canada, 3303-33 Street NW, Calgary, Alberta
[2.] FG&Partners LTD, 219 Hawkside Mews, NW, Calgary, Alberta
(email: Keith.Dewing@Canada.ca)

INTRODUCTION

The Geomapping for Energy and Minerals program of the Geological Survey of Canada is undertaking a review of aspects of the geology of Axel Heiberg Island in Canada's High Arctic Islands. The existing maps are from the early 1970s and they do not include most of the igneous rocks in the area (Thorsteinsson, 1974). The igneous rocks on Axel Heiberg are mainly sills, and at the time of mapping, sills were viewed as an alteration rather than primary map unit.

The goals of the GEM activity on Axel Heiberg Island are to better understand the ages and distribution of igneous rocks, their mineral potential, and the impact of igneous intrusions on evaporite diapirs, organic rich sedimentary rocks and petroleum systems.

This report presents preliminary results, based on archival samples and a small set of new samples, on the impact of igneous rocks on hydrocarbon systems.

GEOLOGICAL CONTEXT

Deposition of the Sverdrup Basin started in the Early Carboniferous with restricted marine clastic sedimentary rocks overlain by a succession of evaporites and deep-water shale. These evaporite layers are the source for the numerous salt structures which pierce, and in some cases on-lap, Mesozoic and Cenozoic rocks along the axis of the basin (Balkwill, 1978).

Extentional tectonics ended during the late Middle Permian, leading to a phase of slower, post-rift crustal subsidence that was driven by thermal contraction and sediment loading. This phase continued relatively uninterrupted until the Middle Jurassic, filling the basin with several kilometers of siltstones and shales. Most notable of these Mesozoic strata are the shales of the middle and upper Triassic Schei Point Group because of their source rock potential (Fig. 2; Brooks et al., 1992).

By Early-Middle Jurassic time, rift activity related to the initiation of the Amerasia Basin to the northwest began to affect the development of the Sverdrup Basin. During the Early Cretaceous, rifting in the Amerasia Basin peaked with the creation of oceanic crust and widespread igneous activity (Embry and Beauchamp, 2008).

Strata deposited during the volcanic episodes were sandstone and siltstone of the Isachsen Formation, shale of the Christopher Formation, sandstone and siltstone of the Hassel Formation and organic-rich mudstone of the lower Kanguk Formation (Evenchick et al., 2015).

The Upper Cretaceous, upper part of the Kanguk Formation grades into coarser clastic units of the overlying Cretaceous to Eocene Eureka Sound Group. These units were deposited in a developing foreland basin that prograded from the northeast.

In its final phase of development, the Sverdrup Basin was uplifted and inverted during the Eurekan Orogeny. This orogenic event occurred in response to sea floor spreading in the Labrador Sea and Baffin Bay which caused the counter clock-wise rotation of Greenland relative to North America. Ongoing movements between these two plates eventually resulted in collision between northeastern Ellesmere Island and western Greenland with compressional phases between 61 Ma and about 41 Ma (Harrison et al., 1999).

PETROLEUM SYSTEMS IN THE SVERDRUP BASIN

During the exploration effort between 1969 and 1986, 119 wells were drilled into Mesozoic structures in the Sverdrup Basin (Rayer, 1981; Chen et al., 2000). This resulted in the discovery of 19 petroleum fields within a fairway extending from Ellef Ringnes Island, southwest to northeastern Melville Island (Fig. 1). Almost all discoveries are within salt-cored, structural traps.

Most oil and gas accumulations are found in Upper Triassic to Lower Jurassic sandstones of the Heiberg Formation, and are sealed beneath Jameson Bay Formation shales (Fig. 2; Rayer 1981). Hydrocarbon accumulations within these formations were sourced primarily from Middle Triassic shales (Brooks et al., 1992)

IGNEOUS ROCKS

Igneous rocks are most commonly found in the northeastern part of the Sverdrup Basin, where they are also the thickest and have the longest age range. Igneous rocks are less common in the southwestern part of the basin, where they are exclusively sills and typically are present lower in the stratigraphy.

Age estimates of volcanogenic rocks are based on biostratigraphy and radiometric techniques. The oldest flows are in the Late Valanginian to Barremian, and the youngest are Upper Cretaceous to Paleocene bimodal alkaline volcanism that is preserved only on northwest Ellesmere Island. Radiometric dates for Sverdrup Basin magmatism yields Ar-Ar and K-Ar dates that range from 144 to 95 Ma (Evenchick et al., 2015; Jowitt et al, 2014).

IMPACT OF IGNEOUS ACTIVITY ON PETROLEUM SYSTEMS

Igneous dykes and sills will locally destroy or create hydrocarbons depending on the width of the thermal halo where igneous rocks intrude source rocks. Magma preferentially intrudes shale, especially the organic-rich Triassic units of the Schei Point Group, which is the source of most of the discovered oil and gas in the Canadian Arctic Islands.

The relative timing of sill emplacement and hydrocarbon migration is also important. Hydrocarbon potential will remain if the sills did not destroy the source rocks and if regional burial and maturation takes place after sill emplacement

Exploration companies working in the Arctic did relatively little exploration in the NE Sverdrup Basin. Companies considered that areas where intrusions cut the reservoir units had very low petroleum potential (Meneley, 1986).

The relative timing of intrusions vs. hydrocarbon generation and the impact of igneous emplacement on source rocks need to be examined to re-evaluate the hydrocarbon potential in areas of igneous activity.

DYKE SAMPLES

Samples of Triassic Murray Harbour Formation were collected on a bedding plane laterally from the contact with a 1.2 m wide dyke. The dyke is located at 78° 31.046’ N 86° 1.886’ W on the Raanes Peninsula of Ellesmere Island. These samples were sent for Rock-Eval pyrolysis to determine the amount of free hydrocarbon (S1) and the remaining source potential (S2) in relation to the distance from the dyke (Fig. 3). Free hydrocarbons increase, starting around 2.5 m from the dyke wall, reach a maximum between 1.5 and 2.0 m, then decrease towards the dyke as the hydrocarbons were destroyed by heat. The source potential systematically decreases towards the dyke as the indiginous organic matter was converted to hydrocarbons or destroyed.

ROMULUS C-42

Gas was collected from pulverized cutting samples at the time of drilling and analysed for C1-C4. Results from the Romulus C-42 well on Ellesmere Island show the relationship between sills, gas wetness and discovered oil (Fig. 4).

Gas wetness in Romulus C-42 shows a mixed relationship to sills. The uppermost sill (in the Barrow Formation) and the thick sill at ~3800 m seem to decrease gas wetness. Other sills seem to have no impact on gas wetness, implying that these sills predate hydrocarbon migration.

The oil from the drillstem test at ~2850 m in Romulus C-42 has a clean saturate fraction gas chromatograph signal, typical of other discovered oils from the Sverdrup Basin (Fig. 4). It shows no obvious thermal alteration despite being from within the thermally altered zone (see vitrinite reflectance values in green). This also implies that hydrocarbon migration occurred after sill emplacement.

DRAKE POINT D-68

Drake Point D-68 was intruded by granodiorite sills 45 m and 75 m thick. These were emplaced during the Jurassic (160 Ma) and Cretaceous (127 Ma). The maturity gradient prior to sill emplacement based on vitrinite was <1% outside the aureole and increased to approximately 2% near the intrusive zone (Fig. 5). Bitumen reflectance also show a sudden increase from 1.5% outside the aureole to approximately 7.0% near the sill contact The bitumen reflectance prior to the sill emplacement can only be inferred from the bitumen below the lower, younger sill because of poor control on bitumen in the interval just above the upper, older sill.

Reflectance trends above and below the two sills appear to be symmetrical indicating the older sill had fully cooled before emplacement of the younger sill. The metamorphic effects of the sill as determined vertically by reflectance trend can be observed for a distance of up to seven times its thickness. The upper, older sill is approximately 45 m thick and the aureole zone above it has a width of 330 m. The width of the aureole below the sill is difficult to establish because it has been obliterated by the effect of the lower, younger sill. The width of the lower sill is 75 m and the aureole is about 400 m.

CHADS CREEK B-64

Strata of Permian age in Chads Creek B-64 were intruded by 120 m diabase sill dated at 126-129 Ma which increased the reflectance of vitrinite from 0.9% to 1.65% near the contact at 3400 m (Fig. 6). Bitumen reflectance follows extrapolated trend for bitumen in the country rock and shows no response in relation to the sill.

HELICOPTER J-12

Helicopter J-12 well on Ellef Ringnes Island shows different responses in the cuttings gas between the upper sills in the well (intruding Deer Bay and Ringnes formations) compared to the lower sills (Fig. 7). The upper sills show no influence on gas wetness, indicating that the petroleum system was active after sill emplacement. The lower sills affect gas wetness indicating that the hydrocarbon system was present at the time of sill emplacement

CONCLUSIONS

The observation that gas wetness and bitumen reflectance is not affected by all igneous intrusions supports the interpretation that there was an active petroleum system either synchronous with (as suggested by Jones et al., 2007) or post-dating the igneous activity in the northeastern part of the Sverdrup Basin.

The hydrocarbon potential on the northeastern Sverdrup basin should be re-assessed in light of these conclusions

REFERENCES

Balkwill, H.R. 1978. Evolution of Sverdrup Basin, Arctic Canada. American Association of Petroleum Geologists Bulletin, v. 62, p. 1004-1028.

Brooks, P.W., Embry, A.F., Goodarzi, F., and Stewart, R. 1992. Organic geochemistry and biological marker geochemistry of Schei Point Group (Triassic) and recovered oils from the Sverdrup Basin (Arctic Islands, Canada). Bulletin of Canadian Petroleum Geology, v. 40, p. 173-187.

Chen, Z., Osadetz, K.G., Embry, A.F., Gao, H and Hannigan P.K. 2000. Petroleum potential in western Sverdrup Basin, Canadian Arctic Archipelago. Bulletin of Canadian Petroleum Geology, v. 48, p. 323-338.

Embry, A.F., and Beauchamp, B. 2008. Sverdrup Basin. In: A. Miall (ed.) Sedimentary Basins of the World, vol. 5. p. 451-471.

Evenchick, C.A., Davis, W.J., Bedard, J.H., Hayward, N., and Friedman, R.M., 2015. Evidence for protracted High Arctic large igneous province magmatism in the central Sverdrup Basin from stratigraphy, geochronology, and paleodepths of saucer-shaped sills. Geological Society of America Bulletin, v. 127, p. 1366-1390.

Harrison, J.C., U. Mayr, D.H. McNeil, A.R. Sweet, D.J. McIntyre, J.J. Eberle, C.R. Harington, J.A. Chalmers, G. Dam, and H. Nohr-Hansen, 1999, Correlation of Cenozoic squences of the Canadian Arctic region and Greenland; implications for the tectonic history of northern North America: Bulletin of Canadian Petroleum Geology, v. 47, p. 223–254.

Jones, S.F., Wielens, H., Williamson, M-C., and Zentilli, M. 2007. Impact of magmatism on petroleum systems in the Sverdrup Basin, Canadian Arctic Islands, Nunavut, a numerical modelling study. Journal of Petroleum Geology, v. 30, p. 237-256.

Jowitt, S.M., Williamson, M.-C., and Ernst, R.E. 2014. Geochemistry of the 130 to 80 Ma Canadian High Arctic Large Igneous province (HALIP) event and implications for Ni-Cu-PGE prospectivity. Economic Geology, v. 109, p. 281-307.

Meneley, R. 1986. Oil and gas filed in the East Coast and Arctic Basins of Canada. In: M.T. Halbouty (ed.) Future Petroleum Provinces of the World. American Association of Petroleum Geologists, Memoir 40, p. 143-176.

Rayer, F.G. 1981. Exploration prospects and future petroleum potential of the Canadian Arctic Islands. Journal of Petroleum Geology, v. 3, p. 367-412.

Thorsteinsson, R. 1974 Carboniferous and Permian stratigraphy of Axel Heiberg Island and western Ellesmere Island, Canadian Arctic Archipelago. Geological Survey of Canada, Bulletin 224, 115 p., and maps 1298A to 1312A and 1348A.

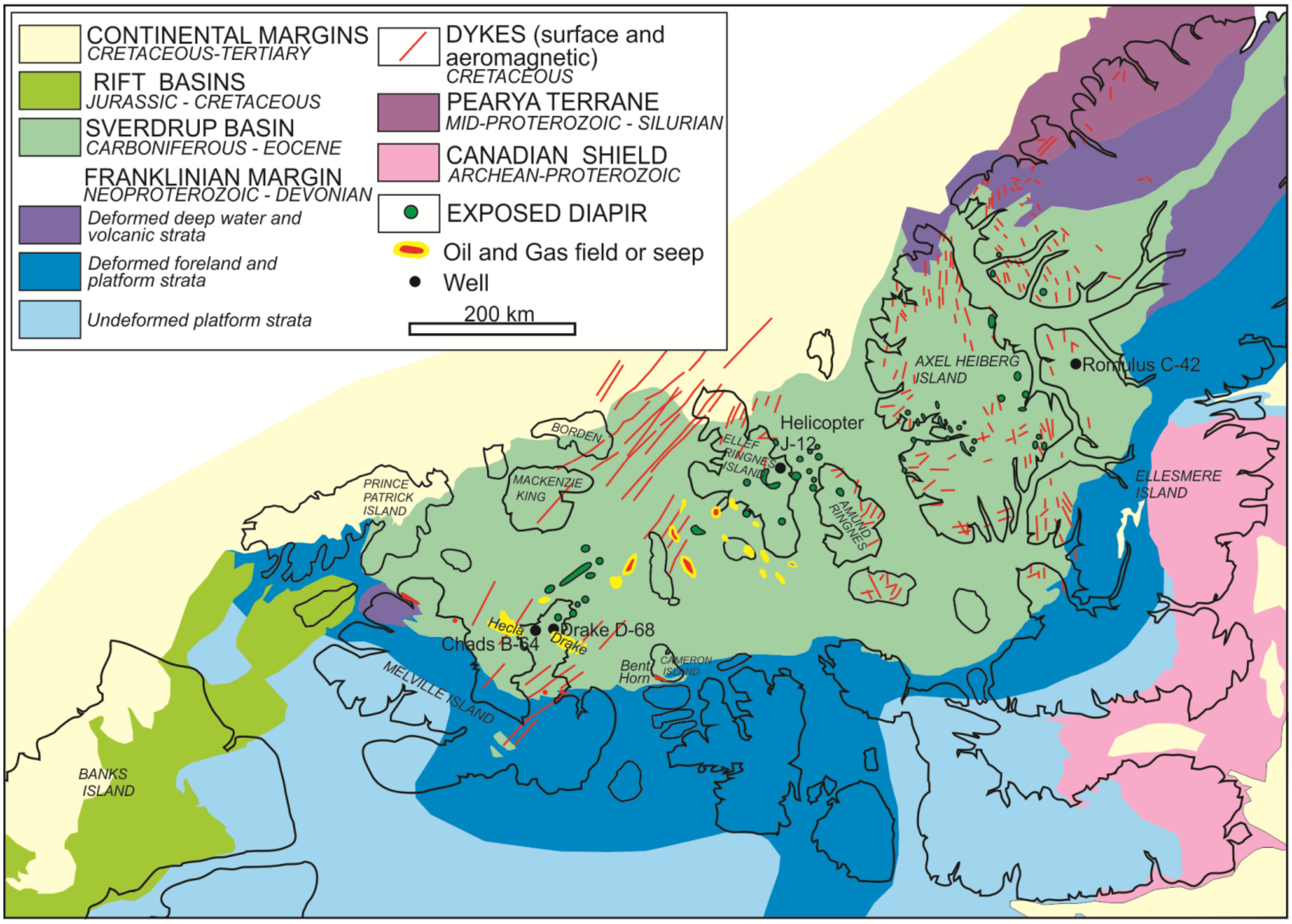

Figure 1. Location of the wells mentioned in the text, shown on a geology map of the northern Canadian Arctic Islands.

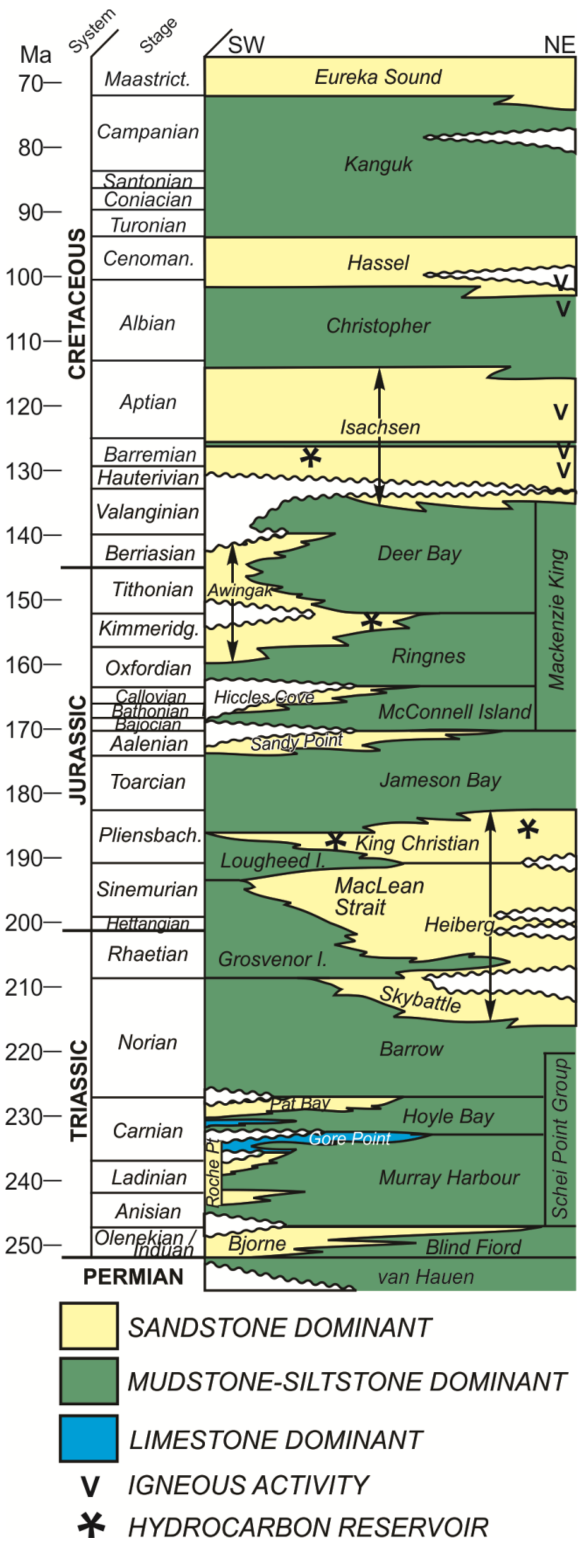

Figure 2. Mesozoic stratigraphy of the Canadian Arctic Islands. After Embry and Beauchamp (2008)

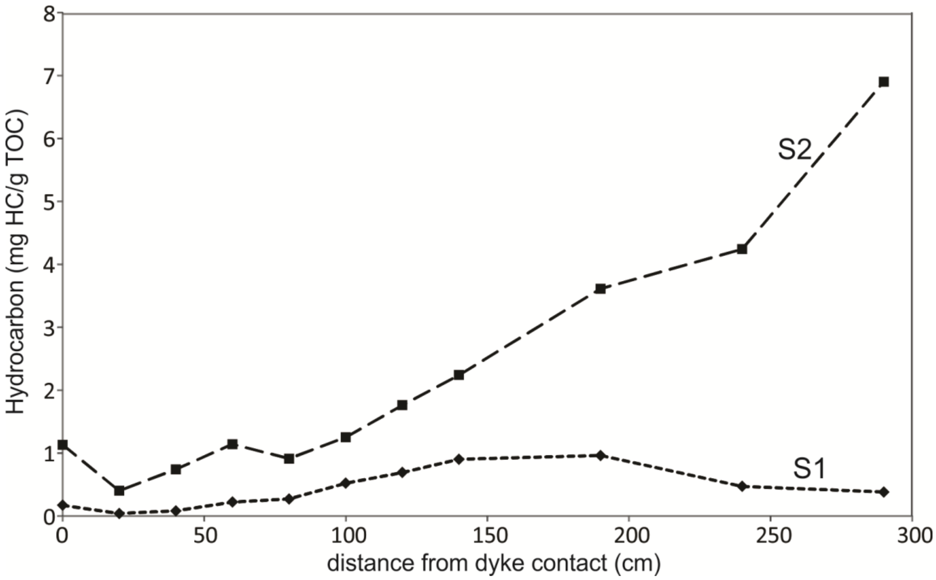

Figure 3. RockEval pyrolysis parameters vary with distance from the contact with a 1.2m wide dyke. S1 denotes free hydrocarbons, S2 is the pyrolysable indigenous organic matter.

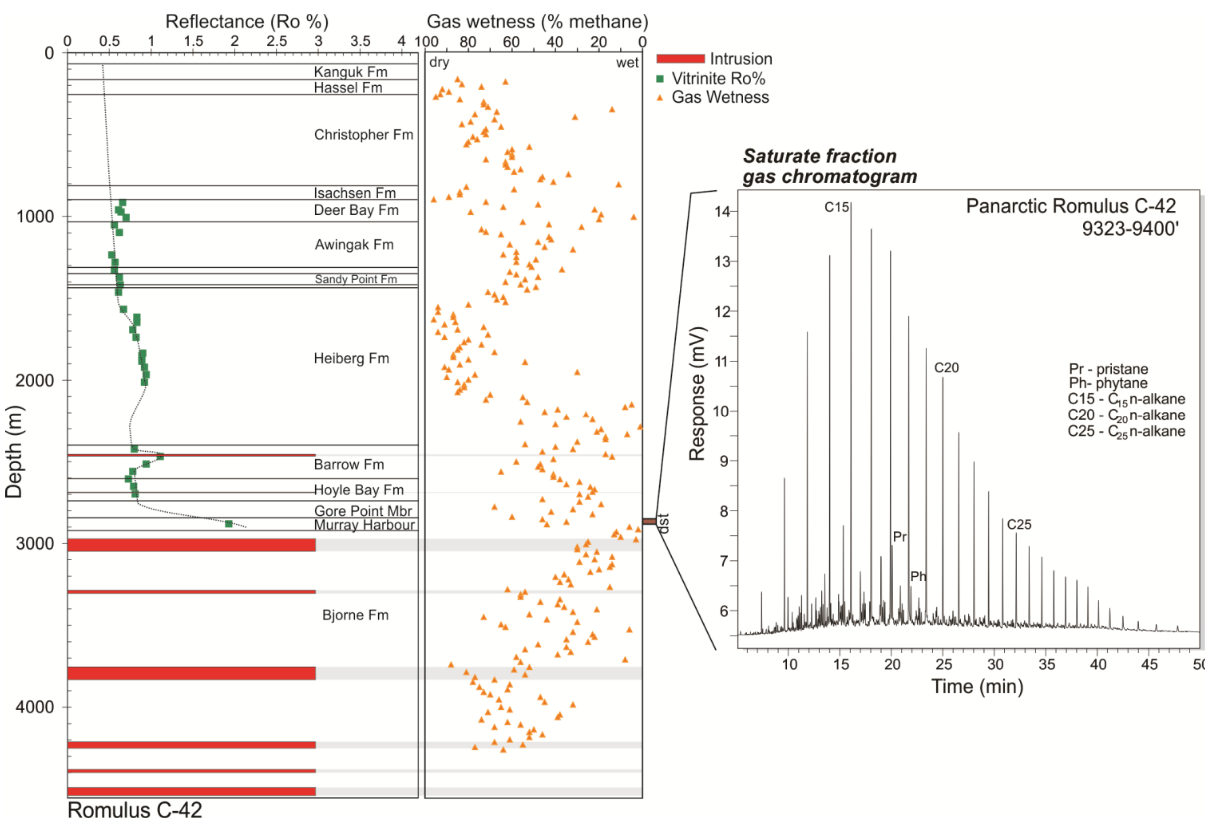

Figure 4. Reflectance and gas wetness of Romulus C-42 well plotted against depth. The recovered oil from near a sill shows no evidence of thermal alteration implying migration after sill emplacement.

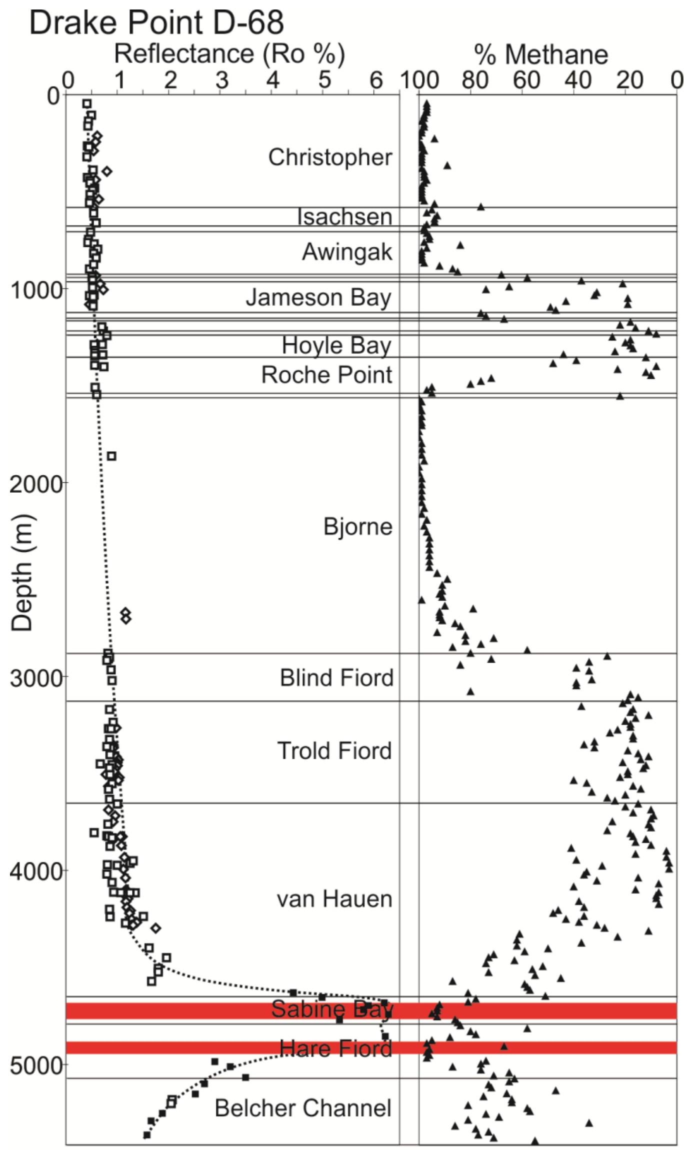

Figure 5. Reflectance and gas wetness (% methane) plotted against depth for the Drake Point D-68 well. Note the impact of the two sills on both reflectance and gas wetness.

Chads Creek B-64

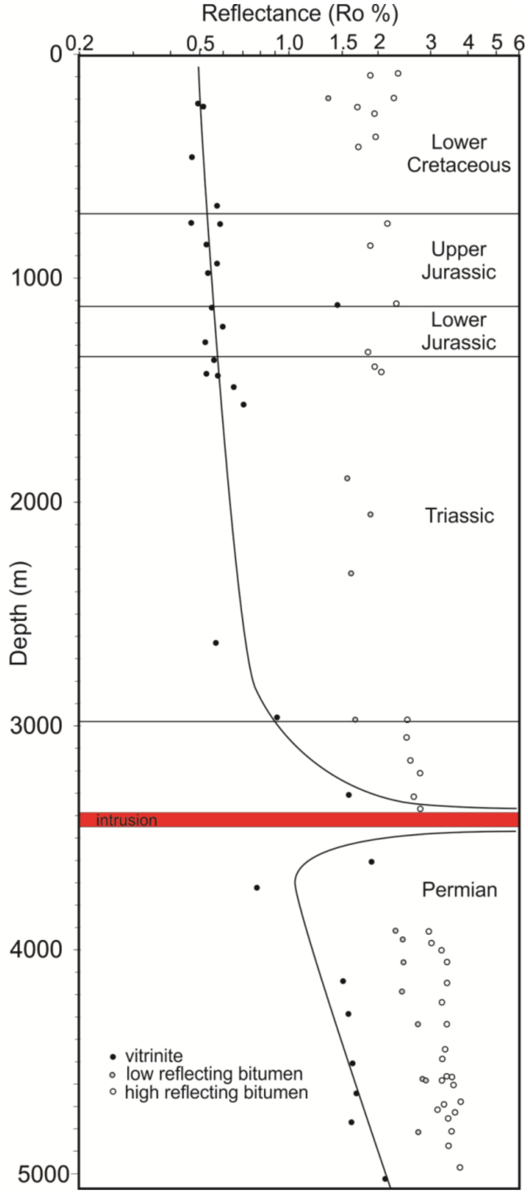

Figure 6. Reflectance of vitrinite and bitumen vs depth for the Chads Creek B-64 well. The reflectance of bitumen seems to be unaffected by the sill, implying that the bitumen formed after the sill was emplaced.

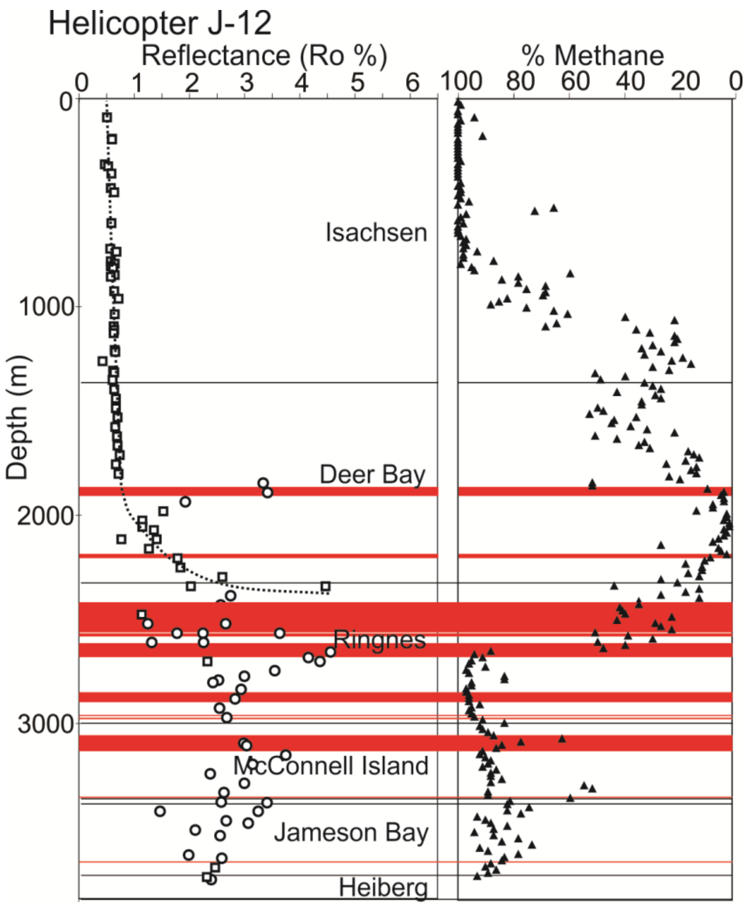

Figure 7. Reflectance and gas wetness (% methane) plotted vs. depth for the Helicopter J-12 well.

MAPPING AND GEOCHRONOLOGY OF ISACHSEN THROUGH HASSEL FORMATIONS ON ELLEF RINGNES ISLAND – IMPLICATION FOR HALIP

C.A. Evenchick[1], W.J. Davis[2], J.H. Bédard[3], N. Hayward[1]
[1.]Geological Survey of Canada, 1500-605 Robson Street, Vancouver, British Columbia
[2.]Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario
[3.]Geological Survey of Canada, 490 de la Couronne, Québec, Québec
(email: Carol.Evenchick@Canada.ca)

INTRODUCTION

A new geological map of Ellef Ringnes Island was a goal identified for the first GEM Western Arctic project. Fieldwork in 2010 and 2011 resulted in two new regional geological maps published at 1:125,000 scale, covering the northern and southern halves of the island (Evenchick and Embry, 2012a,b). The new maps applied current Sverdrup Basin stratigraphic terminology, including subdivision of the Isachsen, Christopher, and Kanguk formations into their respective members. This work was based on seven weeks of fieldwork, and substantial post-field compilation and 'remote predictive mapping', which included examination of aerial photographs and notes of previous workers, potential field data, satellite imagery, and over 12,000 photographs obtained by the senior author during fieldwork.

Ellef Ringnes Island, central Sverdrup Basin, is largely underlain by Lower Jurassic through uppermost Cretaceous marine and nonmarine siliciclastic rocks (Evenchick and Embry, 2012a,b, and references therein; Fig. 1). Mesozoic strata are pierced by seven evaporite diapirs, and are intruded by Cretaceous diabasic sills and dykes of the Queen Elizabeth swarm. In the course of fieldwork and subsequent compilation, newly recognized occurrences and field relationships of igneous rocks prompted a focussed study of the magmatism on the island and what it may contribute to knowledge of the High Arctic Large Igneous Province (HALIP). Publication of that study was the focus in 2014. This paper summarizes the recently published results (Evenchick et al., 2015), and highlights opportunities for further understanding of the HALIP that may be gained by new fieldwork and analysis of igneous rocks on Ellef Ringnes Island.

METHODS

The nature, relationships, and ages of magmatic rocks on Ellef Ringnes Island were documented and interpreted based on: field observations; petrological, geochemical, and geochronological analyses; map compilation; integration of field observations with potential field data; and geophysical modeling (Evenchick et al., 2015). We documented newly recognized occurrences of volcanogenic rocks, presented new U-Pb dates on intrusive and extrusive rocks, and proposed an age-depth analysis of a group of intrusions interpreted to be saucer-shaped sills. The result was an integrated age model for the central Sverdrup Basin that impacts on the significance of the broader HALIP.

INTEGRATED AGE MODEL FOR THE CENTRAL SVERDRUP BASIN

Stratigraphic constraints and radiometric ages indicate six magmatic intervals in the study area between about 130 Ma and 101 Ma (Fig. 2). Ages of emplacement of saucer-shaped sills inferred from their sizes and a model relating sizes to depths of emplacement, are consistent with these ages.

U-Pb Geochronology

Two intrusive rocks were dated. Zircon in a gabbroic rock in Haakon evaporite dome (locality A, Fig. 1) yielded a U-Pb SHRIMP age of 126.6 ± 1.2 Ma, and baddeleyite in a diabasic saucer-shaped sill (locality B, Fig. 1) yielded a U-Pb age of 120.8 ± 0.8 Ma.

Analyses of detrital zircon from volcaniclastic rock at two different localities at the top of Invincible Point Member of the Christopher Formation yielded consistent results. A bentonitic sand (locality C, Fig. 1) yielded rounded zircon with Archean ages and euhedral zircon with Cretaceous ages. Of the Cretaceous ages, one grain has reproducible concordant ages with a weighted mean of 106.2 ± 1.2 Ma and four other grains result in a combined weighted mean of 110.7 ± 1.1 Ma. The hyalotuff (locality D, Fig. 1) resulted in three of four single grain TIMS analyses with overlapping concordant ages with a weighted mean age of 105.4 ± 0.2 Ma, and one older grain at 108 Ma. The results of both rocks agree well with the biostratigraphically determined age for the top of Invincible Point Member (see Evenchick et al., 2015 for discussion and sources of information). This agreement, as well as textural evidence, suggests that the volcanogenic rocks were deposited at 105.4 ± 0.2 Ma (Fig. 2).

Stratigraphic Age Constraints

New occurrences of volcanogenic rocks were found at several localities. The lowest horizon is volcaniclastic rock in the Isachsen Formation (locality E, Fig. 1). Its position, at about mid Paterson Island Member, suggests that it was deposited at about 130 Ma (see Fig. 12 of Evenchick et al., 2015), but could possibly be as old as 135 or as young as 127 Ma. The next highest occurrence is widespread pyroclastic rock at the top of Invincible Point Member of the Christopher Formation. From U-Pb geochronology noted above, it is interpreted to have been deposited at 105 Ma.

Constraints on younger magmatism are exposed south of Cape Cairo (Fig. 2,3). The age of hydroclastic breccia in Macdougall Point Member (locality F, Fig. 1,3), is constrained by it stratigraphic position above the 105.4 ± 0.2 Ma volcanogenic rocks, and below the uppermost Albian base of the Hassel Formation. The latter requires that the breccia be older than the Albian-Cenomanian boundary (100.5 Ma). From its stratigraphic position relative to the top and bottom of Macdougall Point Member (Fig. 12 of Evenchick et al., 2015), the breccia is considered to have been deposited at ca. 103 Ma, but could possibly be as old as 105 Ma or as young as 101 Ma (see Evenchick et al., 2015 for discussion and sources of information).

A breccia unit low in the Hassel Formation (locality G, Fig. 1,3) must be younger than the 105.4 ± 0.2 Ma pyroclastic rocks and also the uppermost Albian biostratigraphic age assigned to the base of the Hassel Formation (ie. possibly as old as ca. 103 Ma). The breccia is interpreted to be stratigraphically below the Albian-Cenomanian (100.5 Ma) sequence boundary that is near mid-section in the Hassel Formation (see Evenchick et al., 2015 for discussion and sources of information). From its stratigraphic position relative to these dated horizons, the Hassel breccia is considered to be ca. 101 Ma, but could be as old as 103 Ma or as young as 100.5 Ma.

Diabasic sills south of Cape Cairo occur about 80 m below, and 150 m above the Chrisotpher-Hassel formation contact (Fig. 3). The upper sill is interpreted to be associated with the immediately overlying Hassel Formation breccia, and therefore emplaced at ca. 101 Ma Evenchick et al., 2015). The lower sill may also be this age, or possibly slightly older, but it is higher stratigraphically than the nearby breccia in Macdougall Point Member, and therefore must be younger than that breccia.

Saucer-Shaped Sills

Diabasic intrusions between Gabbro Peninsula and Louise Fiord occur in oval outcrop patterns (Fig. 1; see Fig. 8 of Evenchick et al., 2015 for detail). This distribution is interpreted to be a result of erosion through the walls and upper rims of saucer-shaped sills. The interpretation is based on the close correspondence of extents of sills with high aeromagnetic anomalies, and observations of subhorizontal bedding truncated by moderately dipping walls of sills. Thirty such intrusions have been identified on land and offshore. They are described and interpreted in Evenchick et al. (2015).

Previous work proposed a relationship between the inner diameter of a saucer-shaped sill and its depth of emplacement (e.g. Polteau et al., 2008). This relationship was used to estimate ages of emplacement for Ellef Ringnes sills by first estimating the depth of emplacement of the dated sill (locality B, Fig. 1). This was achieved by plotting its age on the stratigraphic column (Fig. 12 of Evenchick et al., 2015) – this age indicates an approximate paleosurface level during emplacement; the difference between the paleosurface level and the stratigraphic position of the sill is the depth of emplacement. The depth of emplacement combined with the measured dimensions of the sill results in a single tiepoint on the sill width to depth of emplacement graph of Polteau et al. (2008). In the absence of another dated sill to define a width to depth of emplacement relationship for the Ellef Ringnes intrusions, Evenchick et al. (2015) used assumptions of the one tiepoint for the dated sill and data in Polteau et al. (2008), and published experimental data, to infer depths of emplacement for the other sills. Those depths of emplacement, combined with stratigraphic positions of the sills, were used to derive model emplacement ages for 11 undated saucer-shaped sills. The resulting model ages indicate three intervals of emplacement from ca. 130 to 120 Ma, and possibly younger, and are consistent with ages of magmatism known independently from radiometric dating and the stratigraphic positions of volcanogenic strata (Fig. 2).

Ages of Magmatism Summary

At ca. 131 to 129 Ma, four saucer-shaped sills were emplaced in the Deer Bay Formation at or near the time of deposition of volcaniclastic rocks (Fig. 2). At 126.6 ± 1.2 Ma, magmatism resulted in intrusion of the gabbro at Haakon Dome; two saucer-shaped sills may also have been intruded at about this time. A saucer-shaped sill was emplaced at 120.8 ± 0.8 Ma, at about the same time as intrusion of two other saucer-shaped sills. After ca. 15 m.y., 105.40 ± 0.22 Ma pyroclastic rocks were deposited near the top of Invincible Point Member (Fig. 2). There are no dated intrusions or volcanic events between 120.8 and 105.40 Ma, but the 105.40 Ma volcaniclastic rocks contain older zircon crystals with ages of 110.7 Ma, and 108 Ma. At about 103 Ma, pillow and hydroclastic breccia were deposited in the Macdougall Point Member (Fig. 2). Tabular sills below and above the Christopher-Hassel contact were emplaced at shallow levels at about 101 Ma, with the upper sill being associated with volcanic breccia low in the Hassel Formation.

The results (Fig. 2) show that HALIP volcanism in the Canadian Arctic was more widespread and that magmatic pulses occurred more frequently than was previously known in the Sverdrup Basin. The large range in ages contrasts with the narrow range interpreted for Svalbard and Franz Josef Land by Corfu et al. (2013).

FUTURE WORK

The framework established by the previous work highlights several opportunities to refine ages of magmatism in the central Sverdrup Basin.

Saucer-shaped Sills

The range of sizes of saucer-shaped sills, combined with their stratigraphic positions, may be used to predict emplacement ages (Polteau et al., 2008; Evenchick et al., 2015). The validity of this method as applied to the sills on Ellef Ringnes Island can be tested with high precision radiometric dates of a few sills. Previous work showed that these intrusions may yield datable zircon or baddeleyite. Our approach in future work will be to use legacy data to target sample areas with the coarsest-grained material, and use applicable U-Pb geochronology methods. The one dated saucer-shaped sill (120.8 ± 0.8 Ma, locality B, Fig 1) is assumed to be representative of group 2 sills as identified in Evenchick et al. (2015). To test the validity of the age-depth interpretation and explore the full range of ages represented by the saucer-shaped sills, we would sample sills in each of the other groups, as well as sills with outlier sizes that may represent significantly younger intrusion.

Bentonites in Christopher Formation

Dating of bentonitic rocks near the top of Invincible Point Member on Ellef Ringnes Island (Evenchick et al., 2015), and on Axel Heiberg Island (Herrle et al., 2015), has yielded dates that were not previously recognized in

Sverdrup Basin rocks. Examination of field photographs of Ellef Ringnes Island suggests that there may be stratigraphically higher bentonitic rocks. Analyses of these may add additional ages of magmatism in this poorly documented interval.

Macdougall Point Extrusive/Intrusive Rock

South of Cape Cairo, a resistant ridge of dark blocky weathering rock traces from near the southeast limit of the hydroclastic breccia in Macdougall Point Member, downsection to near the lower contact of the member (locality H, Fig. 3). It has not been examined in the field; based on its weathering nature compared to local sedimentary rock, it is interpreted to be igneous (Evenchick et al., 2015). Field examination would resolve whether it is intrusive or extrusive rock. If it is intrusive, it must be younger than, or the same age as, the highest strata that it intrudes – ie. near the base of the hydroclastic breccia. It may be a dyke associated with the hydroclastic breccia. If it is extrusive rock, it would indicate near continuous local magmatism through much of the history of deposition of the Macdougall Point Member.

Ca. 101 Ma or Younger(?) Sills

The two sills south of Cape Cairo (Fig. 3) are the youngest intrusions in this part of the Sverdrup Basin. Their maximum age is constrained by the age of their host rock, and therefore loosely by regional biostratigraphy (Fig. 2). In addition, the upper sill is interpreted to be associated with the immediately overlying breccia in the Hassel Formation, which more specifically restricts it to the age of the lower Hassel Formation. This relationship should be examined in more detail. Analysis of photographs of the upper sill farther southeast suggest that there may be extrusive rocks locally associated with, or at the same stratigraphic level as the sill. Examination of those areas may resolve the intrusive-extrusive relationships at this horizon. Evenchick et al. (2015) suggested that the lower sill is either the same age of the upper sill, or slightly older. It should be examined and sampled for suitable material for U-Pb dating.

Magnetic Susceptibility Studies

Magnetic remanence measurements (direction and intensity) on oriented samples may contribute to constraints on the age of magmatism by determining the magnetic polarity of the sills. In addition, magnetic remanence data combined with in-situ and sample susceptibility measurements will enhance the accuracy of magnetic models in estimating sill thickness and depth.

CONCLUSIONS

Regional mapping and follow-up analyses in the GEM I project yielded new data and interpretations on the ages of magmatism in the HALIP. New fieldwork focussed specifically on magmatism has the potential to build on knowledge gained in the earlier work to further define the temporal and geographic distribution of ages of HALIP magmatism. An example which may be unique to Ellef Ringnes Island is the saucer-shaped sills. Other areas of such intrusions may be identified, but it is unlikely that many will be found in areas of subhorizontal bedding - a requirement for employment of the sill width to depth of emplacement analysis.

REFERENCES

Avison, H.A., 1987. Ar-40/Ar-30 age studies of mafic volcanics from the Sverdrup Basin, Arctic Canada [B.Sc. thesis]; Halifax, Dalhousie University, 88 p.

Balkwill, H.R. and Haimila, N.E., 1978. K/Ar ages and significance of mafic rocks, Sabine Peninsula, Melville Island, District of Franklin; Geological Survey of Canada Paper 78-1C, p. 35-38.

Corfu, F., Polteau, S., Planke, S., Faleide, J.I., Svensen, H., Zayoncheck, A., and Stolbov, N., 2013. U–Pb geochronology of Cretaceous magmatism on Svalbard and Franz Josef Land, Barents Sea Large Igneous Province; Geological Magazine, v. 150, p. 1127-1135, doi:10.1017/S0016756813000162.

Embry, A., and Beauchamp, B., 2008. Sverdrup Basin, *in* Miall, A.D., ed., Sedimentary Basins of the United States and Canada: Elsevier, p. 451-471.

Estrada, S., and Henjes-Kunst, F., 2013. ^{40}Ar-^{39}Ar and U-Pb dating of Cretaceous continental rift-related magmatism on the northeast Canadian Arctic margin; Zeitschrift der Deutschen Gesellschaft für Geowissenschaften, v. 164, p. 107-130.

Evenchick, C.A. and Embry, A.F., 2012a. Geology, Ellef Ringnes Island north, Nunavut; Geological Survey of Canada Canadian Geoscience Map 86 (preliminary), scale 1:125,000, 1 sheet, doi:10.4095/291565.

Evenchick, C.A. and Embry, A.F., 2012b. Geology, Ellef Ringnes Island south, Nunavut; Geological Survey of Canada Canadian Geoscience Map 87 (preliminary), scale 1:125,000, 1 sheet, doi:10.4095/291566.

Evenchick, C.A., Davis, W.J., Bédard, J.H., Hayward, N., and Friedman, R.M., 2015. Evidence for protracted HALIP magmatism in the central Sverdrup Basin from stratigraphy, geochronology, and paleodepths of saucer-shaped sills; Geological Society of America Bulletin, doi: 10.1130/B31190.1

Herrle, J.O., Schröder-Adams, C.J., Davis, W., Pugh, A.T., Galloway, J.M., and Fath J. 2015. Mid-Cretaceous High Arctic stratigraphy, climate, and Oceanic Anoxic Events; Geology, doi:10.1130/G36439.1

MacRae, R.A., Hills, L.V. & McIntyre, D.J., 1996. The paleoecological significance of new species of *Limbicysta* (Acritarcha) from the upper Albian of the Candian Arctic Islands; Canadian Journal of Earth Sciences, v. 33, p. 1475–1486.

Polteau, S., Mazzini, A., Galland, O., Planke, S., and Malthe-Sørenssen, A., 2008. Saucer-shaped intrusions: Occurrences, emplacement and implications; Earth and Planetary Science Letters, v. 266, p.195–204.

Tarduno, J.A., Brinkman, D.B., Renne, P.R., Cottrell, R.D., Scher, H., and Castillo, P., 1998. Evidence for extreme climatic warmth from Late Cretaceous Arctic Vertebrates; Science, v. 282, p. 2241-2244.

Villeneuve, M., and Williamson, M.-C., 2006. ^{40}Ar-^{39}Ar dating of mafic magmatism from the Sverdrup Basin magmatic province, *in* Scott, R.A., Thurston, D.K., eds., Proceedings of the Fourth International Conference on Arctic Margins; U.S. Department of the Interior, OCS Study MMS 2006-003, p. 206-215.

Williamson, M.-C., 1988. The Cretaceous Igneous Province of the Sverdrup Basin, Canadian Arctic: Field Relations and Petrochemical Studies [Ph.D. thesis]; Halifax, Dalhousie University, 417 p.

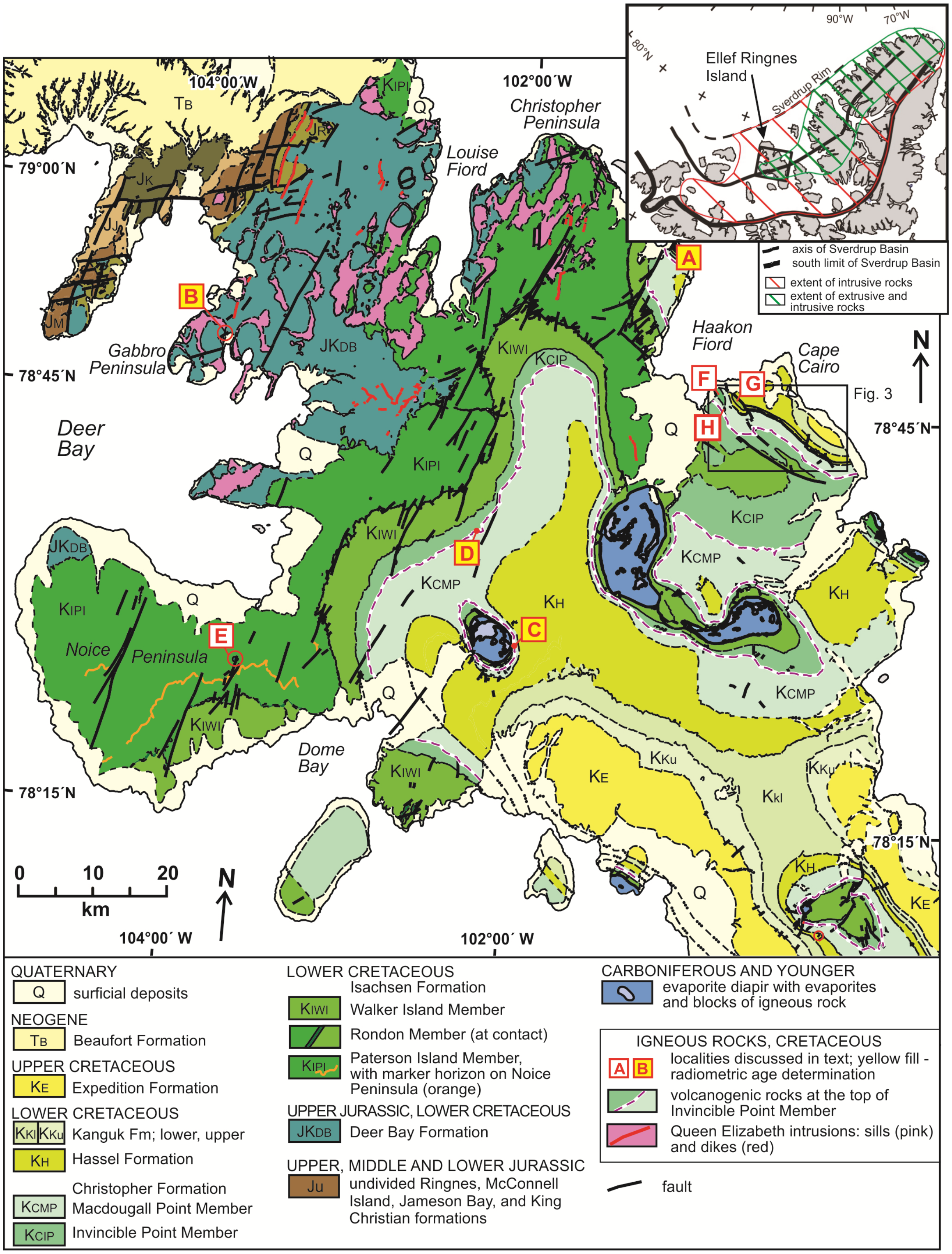

Figure 1. Bedrock geology of central Ellef Ringnes Island, showing the distribution of volcanogenic and intrusive units, and localities discussed in text, modified from Evenchick et al. (2015). Inset shows the location of Ellef Ringnes Island in the Canadian Arctic Islands and the outline of the Sverdrup Basin with distribution of intrusive and extrusive rocks, from Embry and Beauchamp (2008), with the southwest limit of extrusive rocks modified after the results of Evenchick et al. (2015).

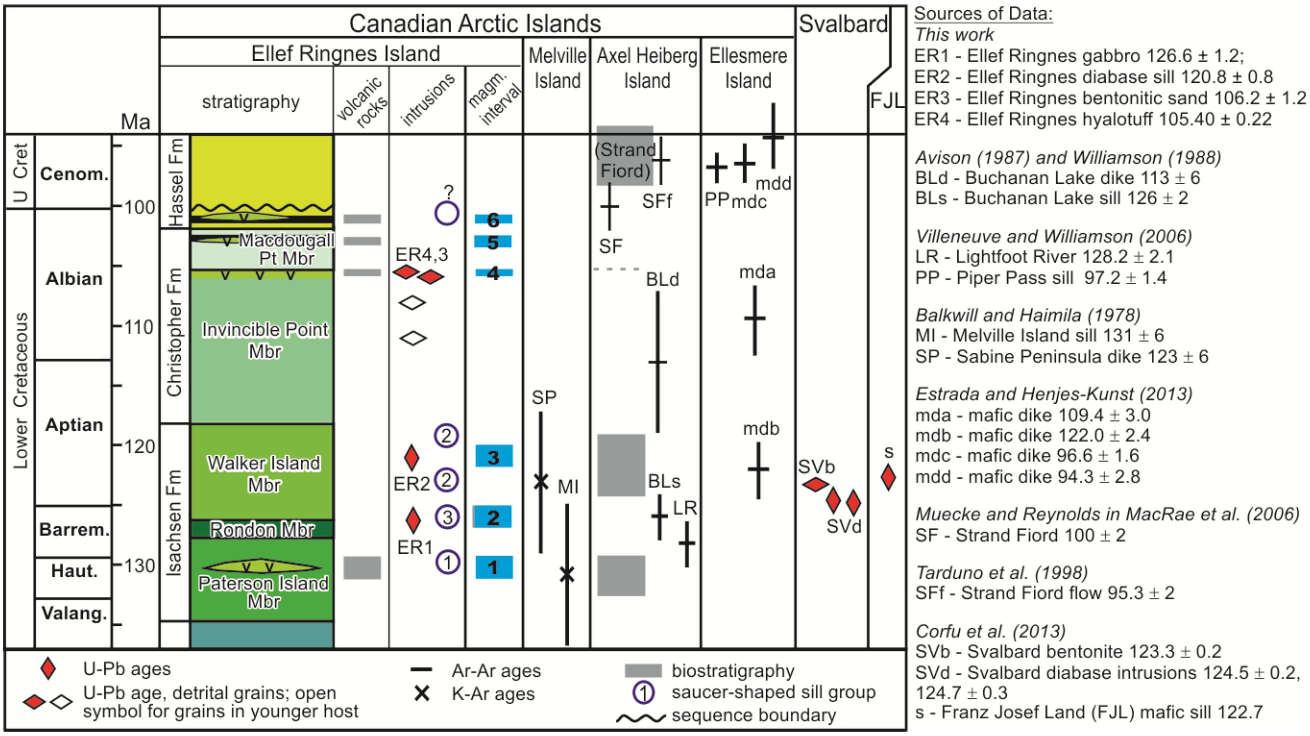

Fig. 2 Summary of the stratigraphic positions of volcanogenic rocks and radiometric ages of intrusive and extrusive rocks for the tholeiitic phase of HALIP magmatism, comparing the new Ellef Ringnes data to elsewhere in the Canadian Arctic, and its closest neighbours, Svalbard and Franz Josef Land (FJL). Modified from Evenchick et al. (2015).

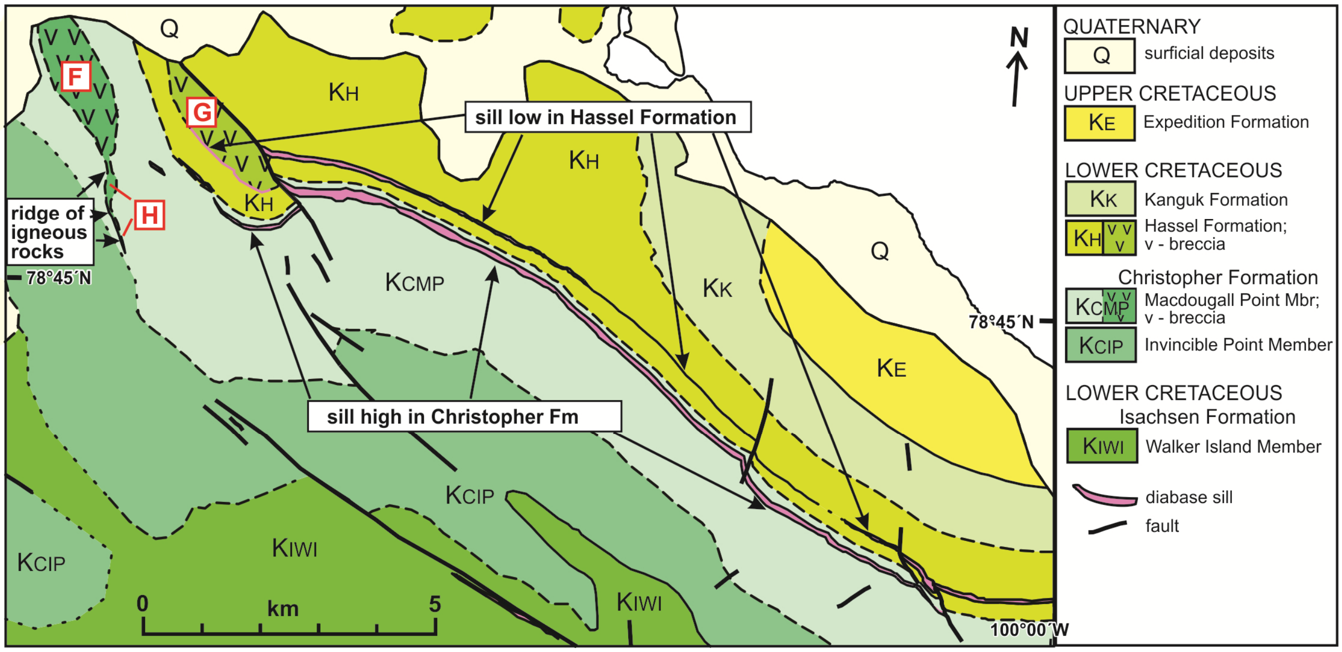

Figure 3. Geology south of Cape Cairo, showing the detailed relationships of breccia units and sills to the Christopher and Hassel formations, from Evenchick and Embry (2012a).