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Mineralization Potential in Volcanic Rocks of the Strand Fiord Formation and Associated Intrusions, Axel Heiberg Island, Nunavut, Canada

M.-C. Williamson and R.A. MacRae

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Canada

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Foreword

This report describes a research proposal on the Ni-Cu-PGE mineralization potential of the High Arctic Large Igneous Province (HALIP) in the Canadian Arctic Islands. The report focused on a comparison between the lava flows in the Strand Fiord Formation and the Siberian Traps in the Norils'k region, Russia. The report was distributed to several mining companies in 2001 to receive feedback on the scientific objectives, methodology and timelines of the proposed study. Although the project was not initially funded by the Geological Survey of Canada, it led to (1) several B.Sc. Honours thesis projects (Lyon, 2005; Jones, 2006; Hachkowski, 2011); (2) geochronological studies on HALIP rocks (Villeneuve and Williamson, 2006); (3) renewed interest in the interaction between evaporites and igneous rocks (Jones et al., 2007; Zentilli et al., 2008); (4) and a 4-year multidisciplinary project on gossans (Williamson et al., 2014; Williamson, 2015). The report was an incentive for renewed field investigations on Axel Heiberg Island[1] and for an evaluation of the Ni-Cu-PGE potential of HALIP rocks based on geochemical signatures (Ernst and Buchan, 2010; Jowitt et al., 2014). Ultimately, the unpublished report was cited as the driver for an exploration campaign by Vale Inco Ltd. that led to the discovery of a massive sulphide showing in the region of interest (Goddard, 2010).

In August 2014, an activity focused on the Ni-Cu-PGE potential of HALIP rocks was approved as part of the GEM 2 research program[2] in collaboration with provincial and territorial governments, northerners and their institutions, academia, and the private sector (Figure 1). The activity was formulated in response to renewed interest in magmatic sulphide deposits associated with LIPs on a global scale (e.g. Begg et al., 2010; Lightfoot and Evans-Lamswood, 2015; Barnes et al., in press). Publication of this legacy report will provide GEM 2 participants and collaborators with access to research that underpins the current state of knowledge on the Canadian portion of the HALIP. Field and laboratory studies that are underway continue to build upon and refine the interpretations presented here (Dewing, 2015).

Marie-Claude Williamson
October 30, 2015

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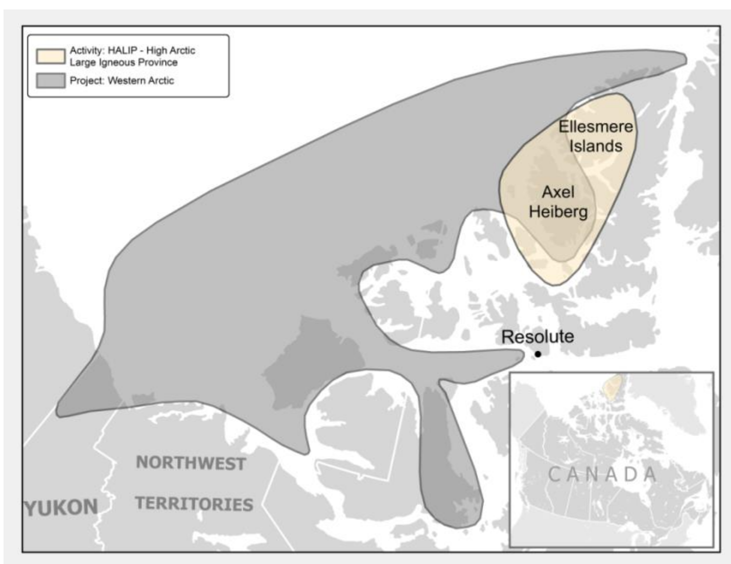

Figure 1. Regional map of the Canadian Arctic Islands showing the area covered by the HALIP Activity within the GEM 2 Western Arctic Region of Interest (2014-2017).

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Project in Development

Mineralization Potential in Volcanic Rocks of the Strand Fiord Formation and Associated Intrusions, Axel Heiberg Island, Nunavut, Canada

Marie-Claude Williamson
and
Andrew MacRae

Geological Survey of Canada (Atlantic)
August, 2001

Canada

Cover illustration :

Thinly bedded and laminated organic carbon-rich mudstone with diagenetic layers of pyrite belonging to the Pilgujarvi, or 'Productive' Sedimentary Formation of the central Pechenga Greenstone Belt, Northwest Russia. The 'Productive Formation' is the host formation for all the ultramafic intrusions and flows with economic Ni-Cu deposits in the region (Melezhik, 1996).

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SUMMARY

The attributes of volcanic rocks and associated intrusives in the Strand Fiord region of Nunavut compare favourably with those of flood basalts hosting the giant massive sulphide deposits in the Noril'sk region of Russia. We propose a new project to develop a GIS decision support tool applied to the search for Ni-Cu-PGE deposits in this region of Canada. The research would be conducted at the Geological Survey of Canada (Atlantic), in partnership with scientists from GSC Iqaluit, GSC Ottawa, and the Canadian Centre for Remote Sensing.

The attached document :

- Presents the planned objectives, deliverables and timetable of the study, and invites comments and suggestions from mining companies at the project development stage;
- Polls the degree of interest from the private sector by soliciting support for the project in writing (email or letter to the address below).

The 3 year project will:

- Integrate multidisciplinary geoscience data and remote sensing information for the Strand Fiord region into a Geographic Information System (GIS) database.
- Groundtruth and calibrate interpretations derived from the GIS tool, that pertain to the Ni-Cu-PGE mineralization potential in outcropping flood basalts and associated intrusions.
- Combine the results obtained from the GIS database and interpretations to compare the attributes of the Strand Fiord flood basalts with those hosting giant Ni-Cu-PGE deposits in the Noril'sk region, providing a decision support tool for mineral exploration in this region.

Key project activities and deliverables include :

- Year 1 - *Phase I* : Integration of several databases into a Geographic Information System (GIS) for the Strand Fiord region, distributed on CD-ROM to participating mining companies, government agencies, and other project collaborators.
- Years 2 and 3 - *Phase II*: Field work on flood basalts of the Strand Fiord Formation and associated intrusions, to groundtruth and expand the interpretations obtained during *Phase I* of the project. GSC Open Files will contain the results of mapping and laboratory measurements, and a report will compare the Ni-Cu-PGE mineralization potential of the flood basalts in the Strand Fiord region with well-documented examples from the giant deposits in Noril'sk, Russia. Mapping and data collection in the Emma Fiord region, northern Ellesmere Island, will investigate the potential for bimodal successions to contain volcanic-hosted massive sulphide (VMS) deposits. GSC Open Files will present the results of mapping and laboratory measurements, and a report will present a preliminary assessment of the Emma Fiord region re: the construction of a second GIS database relevant to VMS exploration.

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1. INTRODUCTION

It is widely accepted that magmatic sulphide deposits are related to igneous bodies emplaced during various stages of the rifting process (Naldrett, 2001). In addition to Nickel (Ni) and Copper (Cu), the orebodies may contain concentrations of the platinum-group elements (PGE) that are of great economic value. During incipient rifting, little or no volcanic activity occurs, as magma generated in the mantle beneath the rift rises through fractures in the crust and forms intrusions and satellite dykes. As rifting progresses, fissure-fed eruptions of predominantly basaltic magma lead to the emplacement of flood basalts that typically fill topographic depressions, failed arms of the rift, or secondary, fault-bounded basins. These thick volcanic piles are associated with sills and dykes that actively intrude the subsiding basin. In failed rifts associated with the formation of a continental margin (e.g. at a triple junction), volcanic activity may be more sporadic, resulting in the formation of a predominantly intrusive igneous province. All of these environments constitute favourable settings for the formation of Ni-Cu-PGE deposits, if (1) sulfur-rich sediments occur in the stratigraphic section and have interacted with mafic magmas; (2) primitive basaltic melts are periodically reinjected in open crustal reservoirs, leading to the enrichment of resident magmas in Ni, Cu and PGE; (3) volcanic feeders provide hydrodynamic traps in which the sulphides can be concentrated to form orebodies.

Several of the attributes listed above are found in the Sverdrup Basin Magmatic Province (SBMP; Fig. 1); and yet, this large region of Nunavut remains virtually unexplored for its economic potential. Most importantly:

- The Sverdrup Basin is an epicontinental rift with a 250 Ma history of sediment accumulation and subsidence.
- Tectonic rejuvenation in the Late Jurassic and Cretaceous is linked to the formation of the polar continental margin and opening of the Arctic Ocean.
- Estimates of the volume of magma erupted (10-20,000 km^3) suggest that the province is comparable in scale to the Columbia River basaltic plateau, of the western U.S. (Williamson, 1988). The volume of magma intruded as sills and dykes is at least an order of magnitude larger.
- Evaporites are a prominent feature of the stratigraphic succession.

In this prospectus, we outline a number of activities to further investigate the potential of the SBMP for hosting Ni-Cu-PGE deposits. These activities include the integration of current geoscience information to produce a GIS decision support tool *(Phase I),* and groundtruthing of the interpretations by conducting field work *(Phase II)*. This project would be part of the Geological Survey of Canada's response to sustainable development commitments in the North (1) by developing an innovative tool that facilitates access to geoscience knowledge for the region, and (2) by quantifying the potential for mineral resources for the benefit of, and management by Northern Canadians.
The document is divided in three parts:

- In section 2, we present some important features of the SBMP, and compare the attributes of flood basalts in the Strand Fiord region of the Sverdrup Basin with those of basalts at Noril'sk, Russia. The massive sulphide deposits at Noril'sk, in the Siberian Traps, are probably the best-documented example of a giant Ni-Cu-PGE deposit associated with continental flood basalts. The similarities between the Siberian Magmatic Province and the SBMP are striking, and listed in detail in section 2.3 of this document.

- In section 3, we outline *Phase I* of the project, consisting of the production of a GIS database from current geoscience information available for the Strand Fiord region.
- In section 4, we introduce some aspects of *Phase II* of the project, involving field work to:

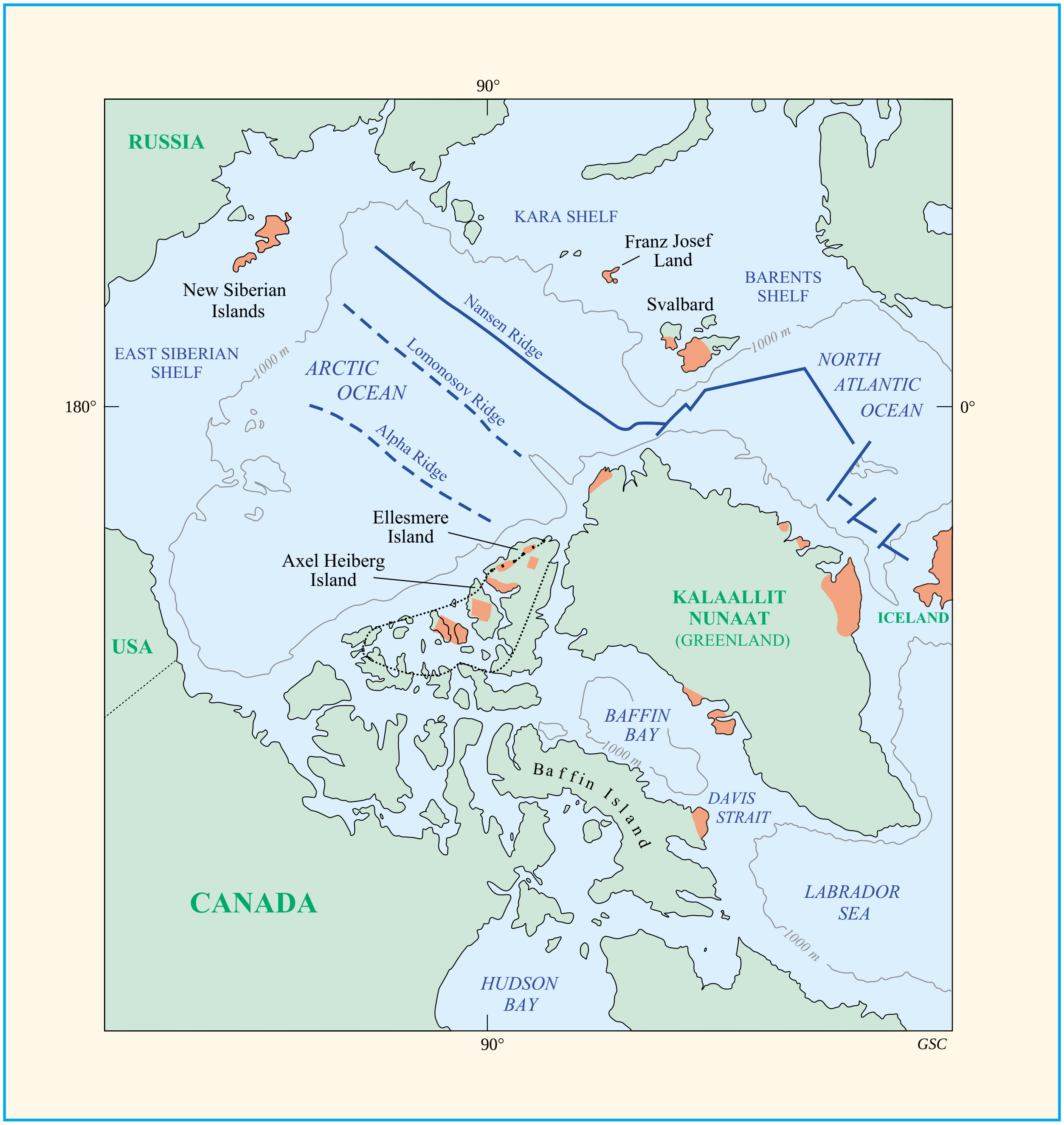

Figure 1. Map of circum-Arctic landmasses showing the position of the Sverdrup Basin in the Canadian Arctic Islands (dotted line). The location of Mesozoic and Tertiary igneous provinces is indicated in red. Major structures in the Arctic Ocean are also shown: full line, active ridge; dashed line, aseismic ridge (modified from Srivastava, 1985).

(1) groundtruth the interpretations obtained from the GIS tool in *Phase I*, and (2) investigate the economic potential of the Emma Fiord region, on northern Ellesmere Island.

This document is not intended to be a comprehensive assessment of the economic potential of the Sverdrup Basin, or a complete overview of the available geoscientific data and interpretations. None of the materials and text have been subjected to the normal editorial process that precedes formal publication. The authors, therefore, take full responsibility for the choice of data, illustrations and interpretations.

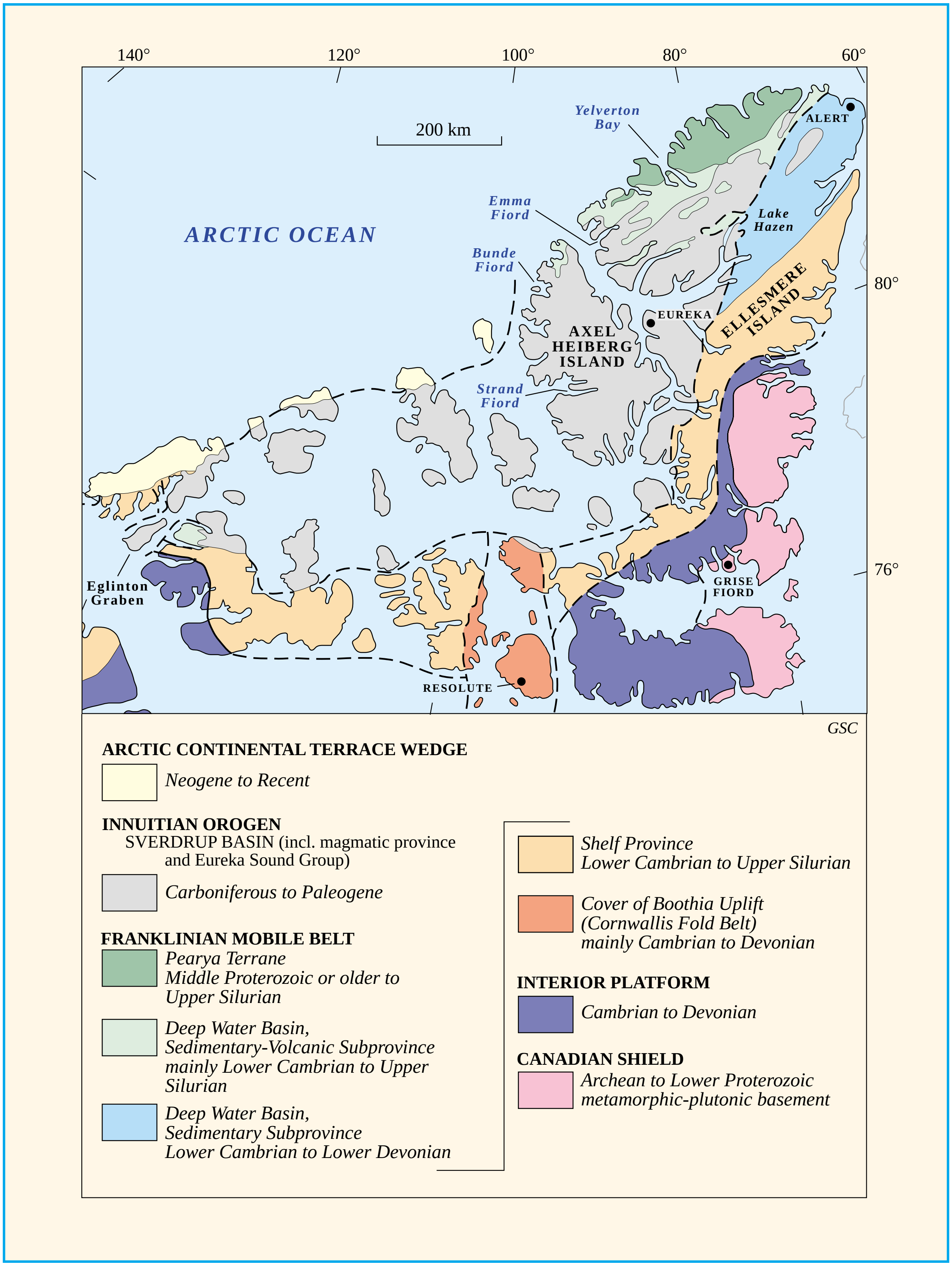

Figure 2. Geological provinces of the Canadian Arctic Islands, Nunavut (modified from Trettin, 1991). Reference is made in the text to volcanic successions located near Strand Fiord, Bunde Fiord, Emma Fiord, and Yelverton Bay.

With these limitations in mind, and in order to serve the interests of our clients and partners from the private sector, government (federal and territorial), and universities, we ask for a written expression of support for the plan, if appropriate, and for your views on the project focus, scientific objectives, methods, and deliverables. (Please refer to Contact Information in the Summary).

2. COMPARISON BETWEEN FLOOD BASALTS AT STRAND FIORD AND NORIL'SK

2.1 Geological Context

The Canadian Arctic Islands contain several geologic provinces that exhibit a general northward-decreasing age (Fig. 2). The Sverdrup Basin is 1,300 km long and 400 km wide (after compressive deformation), and contains up to 13 km of Carboniferous to Tertiary strata. The basin overlies deformed Paleozoic strata, and is shaped by the surrounding fold belts.

The Sverdrup Basin originated during a Carboniferous-Early Permian rifting event that was accompanied by minor volcanic activity. The first direct evidence of renewed rifting consists of a series of minor unconformities in Middle to Upper Jurassic strata, found in the Eglinton Graben, on the northwest margin of the basin (Fig.2). However, the best evidence for renewed rifting accompanied by episodic igneous activity is found in the east-central portion of the Sverdrup Basin.

The Geological Survey of Canada has a long history of geological mapping and investigation in the Canadian Arctic Islands, starting in the 1950's with the pioneering work of '*Operation Franklin*'. A better understanding of the field relations and geochemical character of the SBMP was gained during the

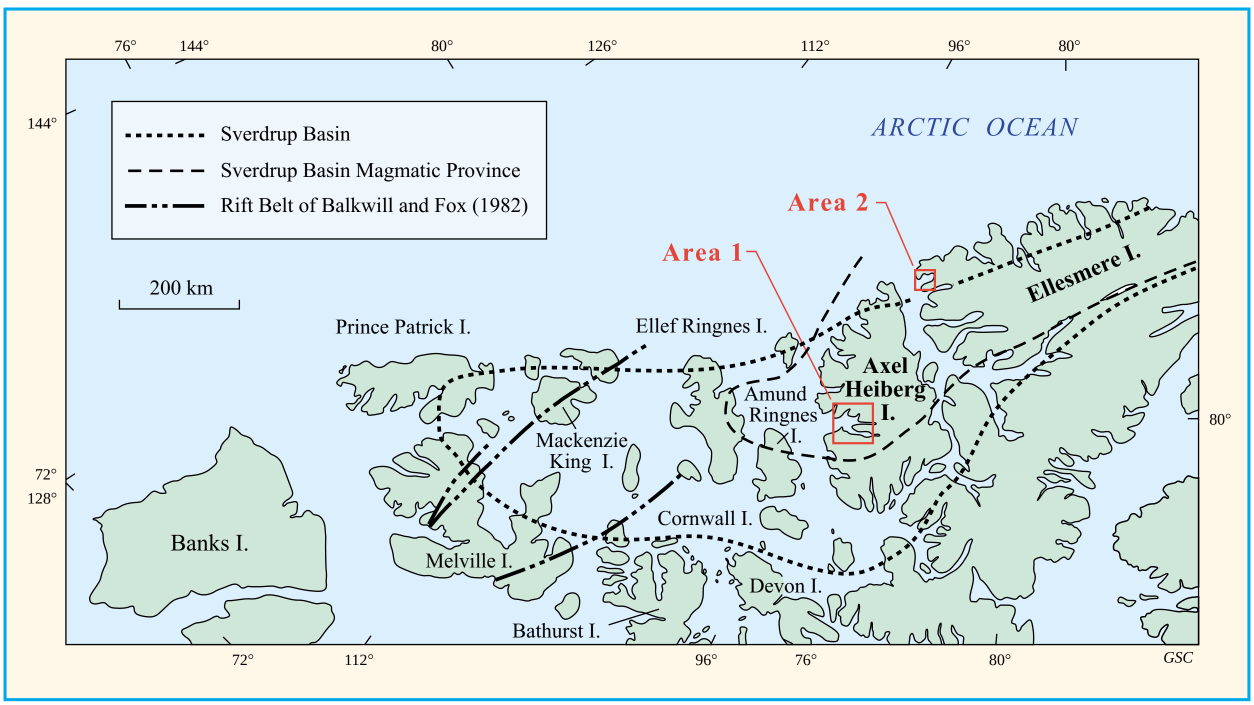

Figure 3. Location of the Sverdrup Basin Magmatic Province (SBMP), in the Canadian Arctic Islands (modified from Embry and Osadetz, 1988). Areas 1 and 2 of this project are discussed in the text. The presence of rift-related structures along a northeast-trending belt in the western Arctic Islands could be linked to Jurassic extension that preceded the emplacement of voluminous magma in the SBMP (Balkwill and Fox, 1982).

1980's through the studies of H.P. Trettin, A. Embry, K. Osadetz (GSC Calgary), M-C. Williamson and A. MacRae (GSC Atlantic), G.K. Muecke (Dalhousie University), and graduate students at the University of Calgary. Hundreds of samples from the SBMP have been collected and analysed, resulting in a substantial database that includes petrographic observations, mineralogy, whole rock geochemistry, isotope systematics, magnetic susceptibility measurements, and $^{40}Ar/^{39}Ar$ age data.

The SBMP as delineated in Figure 3, was emplaced over a period of approximately 45 Ma, starting in the Early Cretaceous. The majority of igneous rocks outcrop on Axel Heiberg Island and northern Ellesmere Island, and consist of flood basalts associated with voluminous, hypabyssal intrusive sheets; thin successions of ferrobasaltic lavas, and associated intrusive rocks; and bimodal volcanic successions of alkaline character containing pyroclastic deposits, and the associated plutons. Igneous rocks are predominantly basaltic, a characteristic of large igneous provinces associated with continental break up (Coffin and Eldhom, 1992). Argon age data suggest that (1) magmatism progressed from areas close to the Mesozoic depocentre (Amund Ringnes Island, Fig. 3) to the northern margin of the basin; and that (2) subalkaline basalts were the first, and most voluminous magmas emplaced in the SBMP. The recognition of older, northeast-trending structures in the western Arctic Islands (Balkwill and Fox, 1982) argues in favour of age-progressive rifting and magmatism in (Fig. 3).

In the next section, we present field evidence for the classification of the Strand Fiord Volcanics as flood basalts, and subsequently compare the attributes of the SBMP with those of the Siberian Magmatic Province in the Noril'sk region of northern Russia.

2.2 Volcanic Stratigraphy of the Strand Fiord Formation

The Strand Fiord Formation consists predominantly of subaerial basaltic lava flows (Souther, 1963). The best evidence for the classification of the lava flows as flood basalts comes from the field observations of Ricketts *et al.* (1985), Embry and Osadetz (1988), Williamson (1988), MacRae *et al.* (1996) and MacRae (1996). On western Axel Heiberg Island, the lava succession consists of a thick succession of ponded lava flows, lapilli tuffs (rare), and volcanic breccia (rare). A photograph of the volcanic pile is shown in Figure 4. Two interpretations of the volcanic stratigraphy are presented in Figures 5 and 6 (Williamson, 1988; MacRae, 1996).

The lava flows are uniformly basaltic, and consist of non-channelized sheets of *aa* and *pahoehoe* flows that display complex intraflow structures as a result of ponding and quenching. Invasive flows occur at the base of the succession (Figs. 5 and 6; Muecke *et al*., 1991), indicating interaction between sheet flows and wet, unconsolidated sediments. Further up in the succession, the lava flows display grey flow tops, suggesting rapid extrusion rates[1]. In some cases, the presence of sedimentary interbeds indicates lacustrine or vegetated terrestrial conditions between volcanic eruptions.

At East Fiord (Fig. 6), an uninterrupted sequence of lava flows with no sediment interbeds or flow-top paleosols measures over 500 metres in thickness (MacRae, 1996). In the Strand Fiord region, the volcanic succession progressively thins to the south and east, where volcaniclastic rocks predominate (Ricketts *et al.*, 1985).

We interpret the physical and textural characteristics of the Strand Fiord volcanics in terms of a flood basalt setting, where the extrusion rate is high, lava flows are ponded in topographic depressions, and uniformly basaltic. These observations are consistent with currently accepted definitions of continental flood basalts. According to Wright (1984), the presence of widespread columnar basalt flows that have interacted with water and sediment, and filled the exisiting topography, is a reasonable indication of flood

[1]Red, oxidized flow tops suggest a longer time interval between volcanic eruptions.

Figure 4. The volcanic succession along Dragon Cliffs, Expedition Fiord (site 3 on the inset map, Fig. 5). The cliff section is over 250 metres in thickness. Photograph by A. MacRae.

basalt, or «*basaltic plains*» volcanism. Self *et al*. (1997) broadly define each lava flow in a flood basalt province as «regional in scale, and formed by a single continuous outpouring of lava».

The Strand Fiord Formation also outcrops on northern Axel Heiberg Island, near Bunde Fiord (Fig. 2). Several geological reports have indicated that the volcanic succession thins dramatically southwards. This is interpreted to represent an overall regression from dominantly marine sedimentary to dominantly terrestrial, volcanic deposition. The north to northwestern part of Axel Heiberg Island represents a proximal volcanic facies and is the source area for the basalt plateau. Fissure-fed lava flows were erupted and prograded southwards, where distal portions of the flows were deposited together with marine facies of the Bastion Ridge Formation (Ricketts *et al*., 1985; MacRae *et al*., 1996).

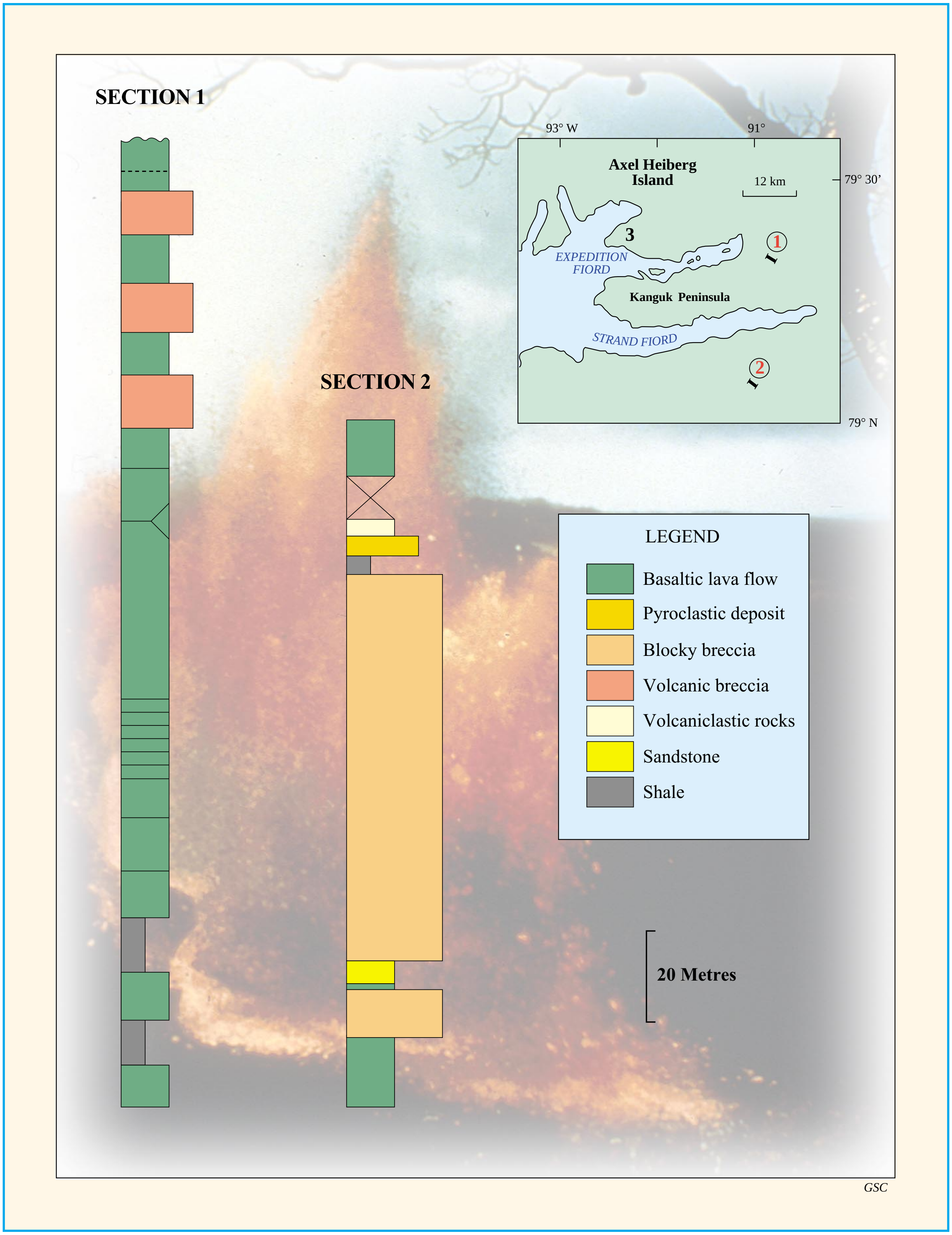

Figure 5. Schematic stratigraphic sections of the Strand Fiord Formation at Bastion Ridge (Section 1) and Glacier Fiord Syncline (Section 2), on western Axel Heiberg Island. Modified from Williamson (1988).

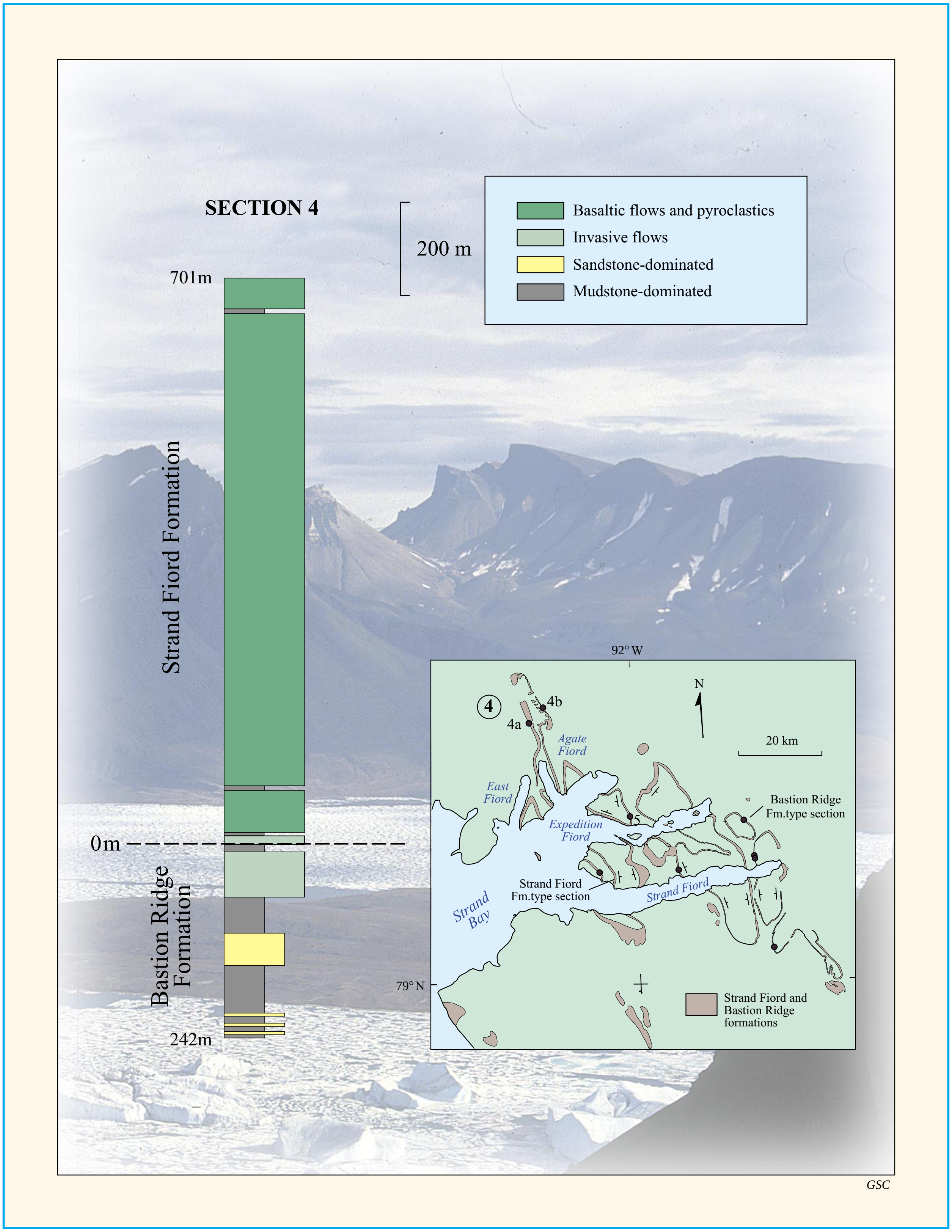

Figure 6. Schematic stratigraphic sections of the Strand Fiord Formation at East Fiord, on western Axel Heiberg Island. The contact between the Strand Fiord Formation and the Bastion Ridge Formation is drawn at the first point in the succession where near-surface intrusion can be clearly demonstrated. Modified from MacRae et al. (1996).

2.3 Comparison with the Noril'sk region, northern Russia

The massive sulphide deposits at Noril'sk, in the Siberian Traps, are probably the best-documented example of a giant Ni-Cu-PGE deposit associated with continental flood basalts. At the present time, the PGE's recovered at Noril'sk and from alluvial sources in Russia, account for the highest supply of Palladium, and second highest supply of Platinum on the world market (Fig. 7).

The Noril'sk tectonic and magmatic setting is summarized in Table 1, under the following headings:

A. Field Observations
- A1. Eruptive Setting
- A2. Host Rocks, Stratigraphy, and Structures

B. Analytical Data
- B1. Petrology and Geochemistry
- B2. Geochronology

C. Geophysical Data

D. Regional Tectonics

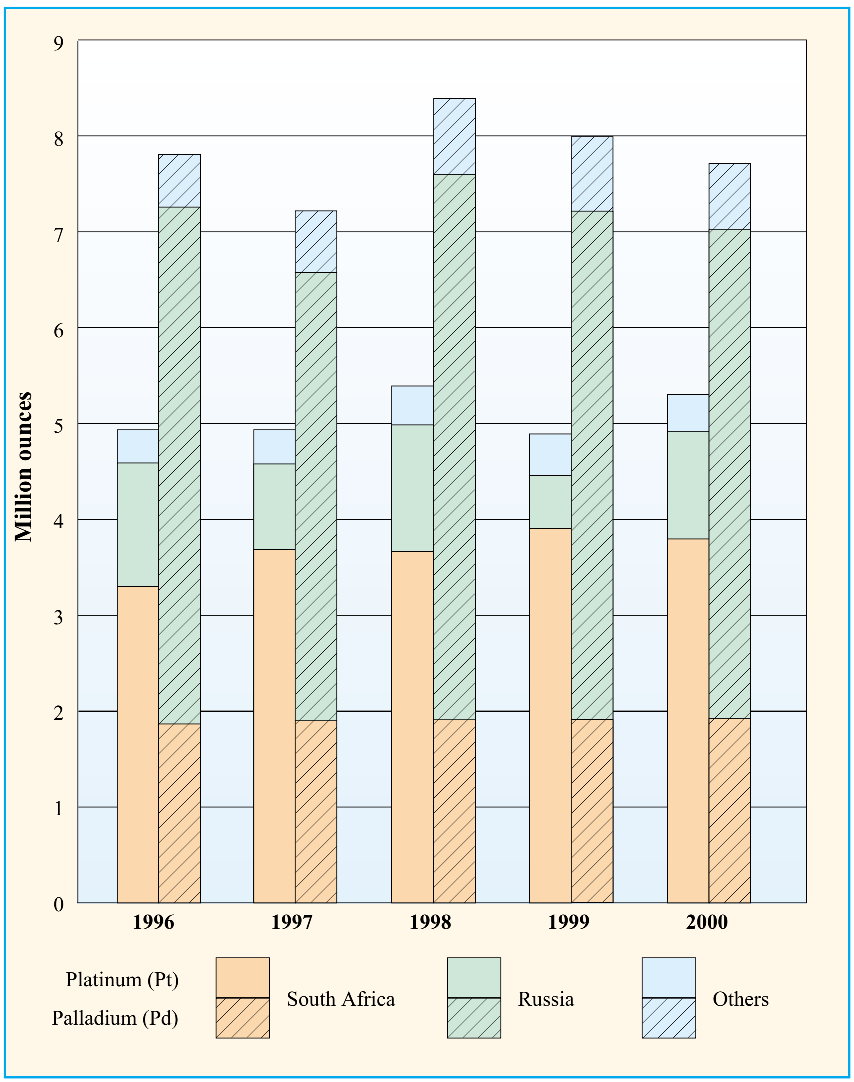

Figure 7. World supply of Platinum (Pt) and Palladium (Pd) for the period 1996-2000, based on statistics released by Johnson Mathey (Platinum|2001, May 2001).

In the table, the attributes of the Siberian Magmatic Province in the Noril'sk region (Naldrett and Lightfoot, 1993; Jefferson *et al*., 1994; Fig. 8) are compared with those of Sverdrup Basin Magmatic Province, with emphasis on the characteristics of Strand Fiord basalts (Ricketts *et al*., 1988; Williamson, 1988; MacRae, 1996).

Table 1
A. FIELD OBSERVATIONS

NORIL'SK REGION, RUSSIA	STRAND FIORD REGION, CANADIAN ARCTIC ISLANDS
A1.1 Flood basalt sequence, measuring up to 3500 m.	Flood basalt sequence, measuring up to 1000 m.
A1.2 Ultramafic rocks are present (1% of the total sequence).	No ultramafic rocks observed to date
A1.3 Volcanic successions associated with voluminous gabbro-dolerites.	Volcanic successions associated with large volumes of magma intruded as sills and dykes.
A1.4 A number of sills are strongly differentiated (peridotite to granophyre).	Some sills are differentiated (gabbro to granophyre).
A1.5 Major sills serve as magma chambers for basalts.	Major sills could have acted as magma reservoirs: Dyke swarms represent the surface expression of magmatic feeders and there is evidence that dykes and sills merge at depth.
A1.6 Some gabbro-dolerites form chonoliths.	Unknown
A2.1 Epicontinental setting.	Intracontinental basin undergoing more than one episode of rifting. Sedimentation terminated by compression in a foreland basin setting.
A2.2 Host strata include shales or granodioritic bodies.	Black shales underlie, and are interbedded with, the flood basalt sequence, and are the host rocks for the associated intrusions.
A2.3 Sulfur-rich country rocks are host to sills; presence of sulfate-bearing evaporites.	Evaporite diapirs are present, and are spatially associated with gabbroic intrusions.
A2.4 Reservoirs of oil and gas are present.	Oil and gas fields have been identified in the region.
A2.5 Structure and stratigraphy record synvolcanic faults.	Synvolcanic faults identified locally, where volcanic successions have been mapped in detail.

GSC

A1. *Eruptive Setting* **A2.** *Host Rocks, Stratigraphy, and Structures*

Table 1 *(cont'd)*

B. ANALYTICAL DATA

NORIL'SK REGION, RUSSIA	**STRAND FIORD REGION, CANADIAN ARCTIC ISLANDS**
B1.1 Presence of mafic and ultramafic magmas, where mafic rocks predominate.	Widespread occurrence of mafic magmas confirmed by geochemical studies.
B1.2 Evidence for "open system" magma chamber processes, including periodical magma recharge.	Evidence for steady state magma chamber processes, and for periodical reinjection of primitive basaltic magma.
B1.3 Evidence of crustal contamination of some of the magmas.	Crustal contamination of the Strand Fiord basalts is indicated by Rb-Sr and Sm-Nd isotope systematics.
B1.4 Association with a mantle plume.	Late stage influence of a mantle plume suggested by the eruptive setting, and magmatic history; confirmed by isotopic data.
B1.5 Chalcophile element depletion in contaminated magmas (Ni and Cu depletion that is not associated with magmatic differentiation).	Ni and Cu depletion in lavas of the Strand Fiord Formation. Extremely depleted values in some younger lavas of the Hassel Formation.
B1.6 Relatively high Cr in sills of economic importance. High values of S, platinum-group elements (PGE), Se or As in sills.	High Cr values reported in some sills. No data available on S, PGE, Se, and As.
B2.1 Igneous province of Permo-Triassic age.	Igneous province of predominantly Cretaceous age.
B2.2 Magmatic activity switched episodically between different eruptive sites.	Geochronological evidence for the migration of magmatic activity from areas close to the depocentre to the northeastern margin of the rift basin.
B2.3 Intrusions are contemporaneous with volcanism – some correlations are possible. The distribution of intrusion types is broadly linked to the location of the maximum thickness of comagmatic lava.	Clear association between volcanic and intrusive rocks, based on field relations, geographic distribution, Argon age data, and geochemical signatures.

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B1. *Petrology and Geochemistry* **B2.** *Geochronology*

Table 1 *(cont'd.)*

NORIL'SK REGION, RUSSIA	STRAND FIORD REGION, CANADIAN ARCTIC ISLANDS
C1. Gravity and magnetic evidence of large, deep mafic bodies.	Susceptibility measurements suggest that magnetic anomalies are associated with the presence of mafic igneous rocks.
C2. Major faults located at the edge of a regional magnetic high indicate a major crustal break.	Under investigation.
D1. Continental-scale rifting, and presence of two rifts at a triple junction.	Continental-scale rifting and links to the development of the proto-Arctic Ocean, have been demonstrated by stratigraphic and structural studies.
D2. Major faults penetrating the lithosphere, which were activated or reactivated during rifting, and appear to have acted as conduits for the magmas, and as loci for the intrusions.	Unknown in the case of the Strand Fiord Formation. Major faults are present in the vicinity of younger volcanic successions in Area 2, Northwest Ellesmere Island.

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C. *Geophysical* **D.** *Regional Tectonics*

As a complement to Table 1, Figures 9 and 10 show a comparison of geochemical data for the Strand Fiord basalts, and from the *Tuklonsky* (Tk) and *Nadezhdinsky* (Nd) formations at Noril'sk (Fig. 8). The two diagrams demonstrate the similarities between the Strand Fiord basalts and the contaminated, chalcophile-element depleted lavas of the Nd lavas (Lightfoot *et al*., 1993; Fedorenko *et al*., 1996).

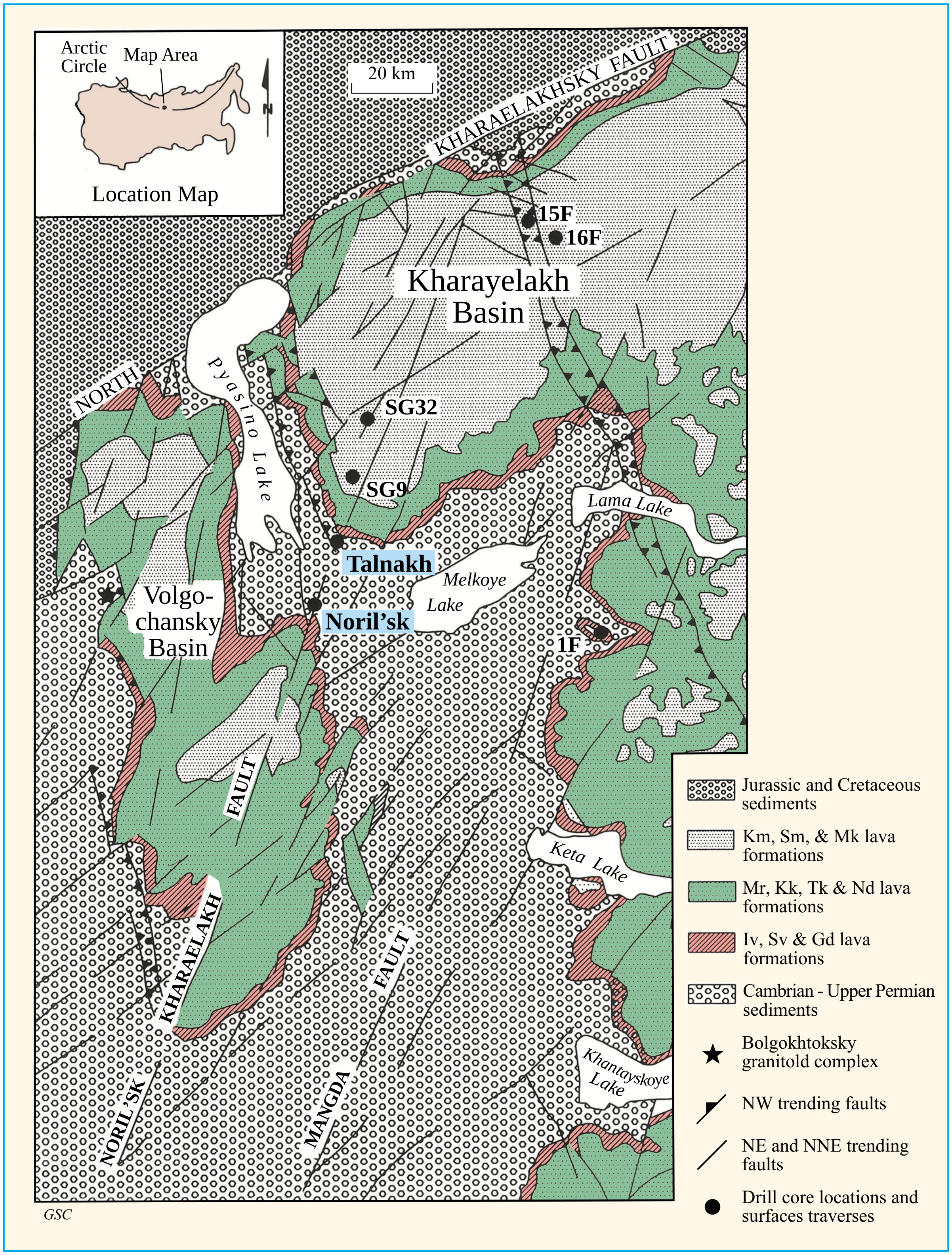


Figure 8. Map of the Noril'sk region, modified from Lightfoot and Hawkesworth (1997). Several formations have been recognized in the Siberian Traps. In Figures 9 and 10, we present a comparison of geochemical data for the Tuklonsky (Tk) and Nadezhdinsky (Nd) formations (Lightfoot et al., 1993; Fedorenko et al., 1996) and for the Strand Fiord basalts on western Axel Heiberg Island (Fig. 5; Williamson, 1988).

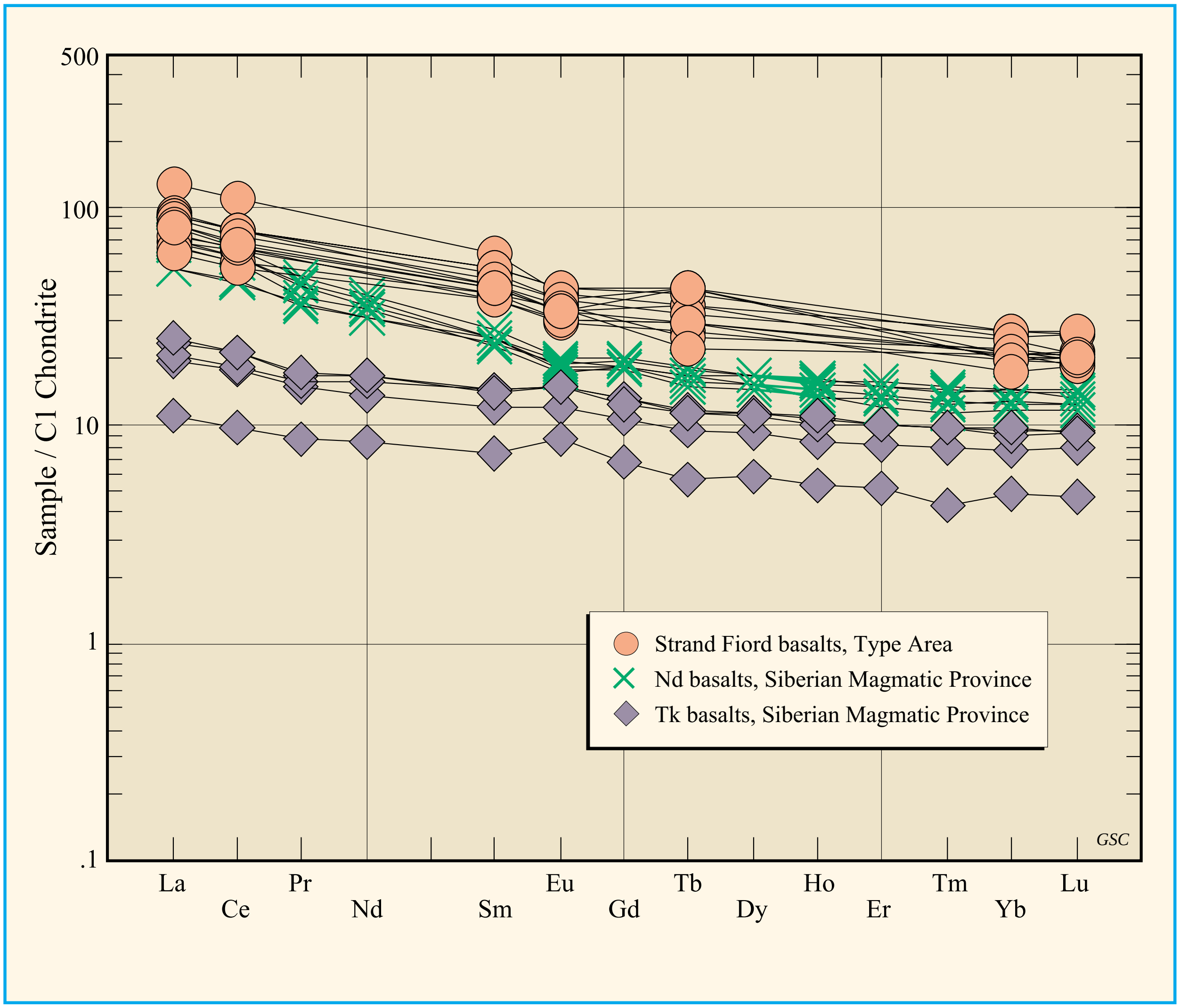


Figure 9. Chondrite-normalized rare earth element (REE) patterns for samples of basaltic lavas from the Strand Fiord Formation (Area 1, Fig. 3), Tk basalts, and Nd basalts (Siberian Magmatic Province). The Tk and Nd lava successions at Noril'sk illustrate metallogenic processes linked to the presence of giant Ni-Cu-PGE deposits. Of the entire volcanic succession in the Siberian Traps, the Nd lavas show the best geochemical evidence of equilibration with sulphides, and appear to have experienced the largest amount of crustal contamination. The Tk basalts illustrate the composition of less contaminated primitive magma, from which the Nd lavas were derived. In this diagram, the REE patterns of Strand Fiord and Nd basalts indicate that these are evolved, contaminated flood basalts with a similar degree of light REE enrichement. Data source : Lightfoot et al. (1993); Fedorenko et al. (1996); Williamson (1988).

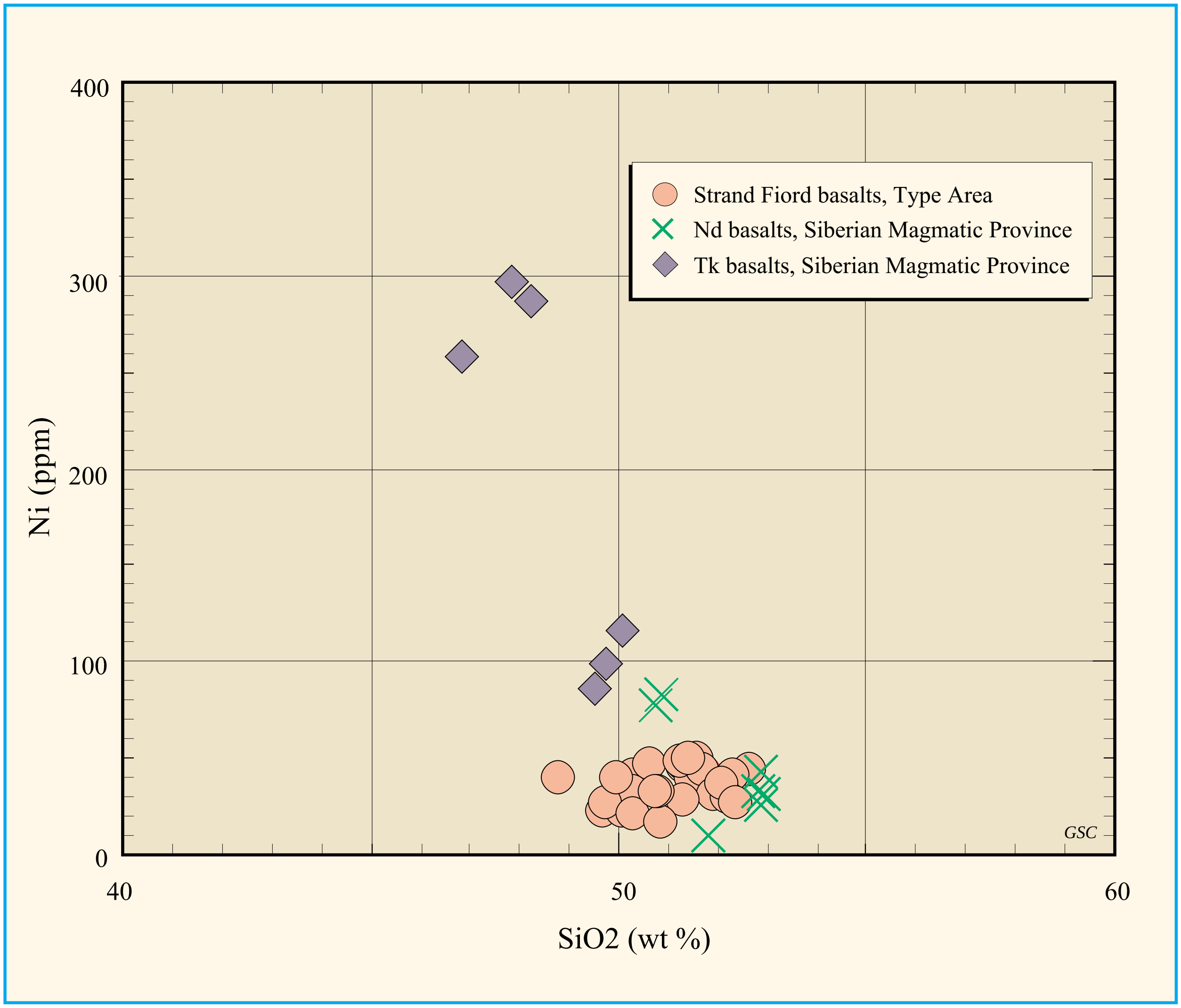


Figure 10. Plot of Ni (ppm) vs. SiO_2 (wt %) for samples of basaltic lavas from the Strand Fiord Formation (Area 1, Sverdrup Basin Magmatic Province), Tk basalts, and Nd basalts (Siberian Magmatic Province). The Tk and Nd lava successions at Noril'sk illustrate metallogenic processes linked to the presence of giant Ni-Cu-PGE deposits. The position of the Strand Fiord and Nd basalts together on this diagram suggests that the magmas could have undergone a similar history of differentiation, crustal contamination, and chalcophile element depletion. Data source : Lightfoot et al. (1993); Fedorenko et al. (1996); Williamson (1988).

In summary, many of the metallogenic features of the Noril'sk region (Naldrett and Lightfoot, 1993) are found in the Strand Fiord region of the Sverdrup Basin Magmatic Province. These features consist of:

1. A hot region in the mantle giving rise to a thick flood basalt sequence (e.g. A1.1, B1.4; Fig. 4, 5, 6).
2. Continental-scale rifting (e.g. A2.1, D1).
3. Syn-volcanic faults, activated or reactivated during rifting, and serving as the conduits for volcanic eruptions and magma intrusions (e.g. A2.5, B2.2, D2).
4. Crustal contamination of some of the magma (B1.3, Fig. 9).
5. Chalcophile element depletion of contaminated magma (e.g. Ni depletion that is not associated with magmatic differentiation and is thus probably due to sulfide segregation; Fig. 10).
6. Intrusion of magma that has inherited sulfide removed from the depleted magma and is, therefore, highly enriched in chalcophile elements (B1.6).
7. The presence of sulfate-bearing evaporites (A2.3).

3. *PHASE 1*: CONSTRUCTION OF A GIS DATABASE FOR THE STRAND FIORD REGION

The comparison between the Strand Fiord and Noril'sk regions (Table 1) leads us to conclude that several factors that are critical to the formation of Ni-Cu-PGE deposits are present in the SBMP. These are:

(1) an extensional regime, and the evidence for the progression of rifting from incipient to mature stages in different parts of the Sverdrup Basin;
(2) sulfur-rich sediments that are present in the stratigraphic section and have interacted with mafic magmas;
(3) primitive basaltic melts that are periodically reinjected in open crustal reservoirs;
(4) volcanic feeders for the flood basalt sequence and asssociated intrusive rocks, where sulphides can be concentrated to form orebodies.

We propose to construct a GIS tool for the Strand Fiord region, to facilitate the application of exploration criteria relevant to the search for Ni-Cu-PGE deposits in flood basalt settings (Naldrett, 1992). Geographic information systems (GIS) provide a visual environment where different types of geoscience datasets can be compiled, integrated, manipulated, analysed, and interpreted to construct « *knowledge-driven* » *models* (Wilkinson *et al*., 1997; Pirajno, 1999; Harris *et al*., 2000). Further integration of geoscience information with remote sensing data increases the versatility of the GIS tool, particularly in arid regions (e.g Asadi and Hale, 1999; Budkewitsch and d'Iorio, 2000).

The Strand Fiord region is one of the best-documented areas in the Canadian Arctic Islands, and constitutes a natural laboratory for GIS applications. Digital databases already in existence include: topographic and geological maps, lithogeochemical data, and potential fields data. Remote sensing data are also available for the region, and would be integrated in the GIS to enhance the geological features observed on base maps (e.g. Wilkinson *et al*., 1997). Stratigraphic, mineralogical, and geochronological data will be digitized during the course of the project.

The resulting GIS tool will enable the user to apply the criteria proposed by Naldrett (1992), such as:

- identify major faults and their intersection with volcanic systems;
- compare and contrast geochemical signatures, giving particular attention to the effects of crustal contamination and the extent of chalcophile element depletion;
- study the intrusions, with special attention given to cross-cutting relationships with volcanic successions;
- single out the intrusions that post-date the emplacement of lavas depleted in chalcophile elements and are closely associated with major, deep-penetrating faults;
- extend the expression of surface features to areas where outcrop is scarce.

The project research activities and deliverables are summarized in Figure 11. The availability of a fully integrated, georeferenced GIS for the Strand Fiord region will:

- facilitate the transfer of geoscience information for this region to federal and territorial agencies, northern communities and the private sector;
- optimize the use of data collected from surface outcrops to apply exploration criteria in the search for Ni-Cu-PGE deposits;
- serve as a model in future mineral exploration activities focused on the covered portions of large igneous provinces.

In the next section, we present some of the activities linked to groundtruthing of interpretations obtained

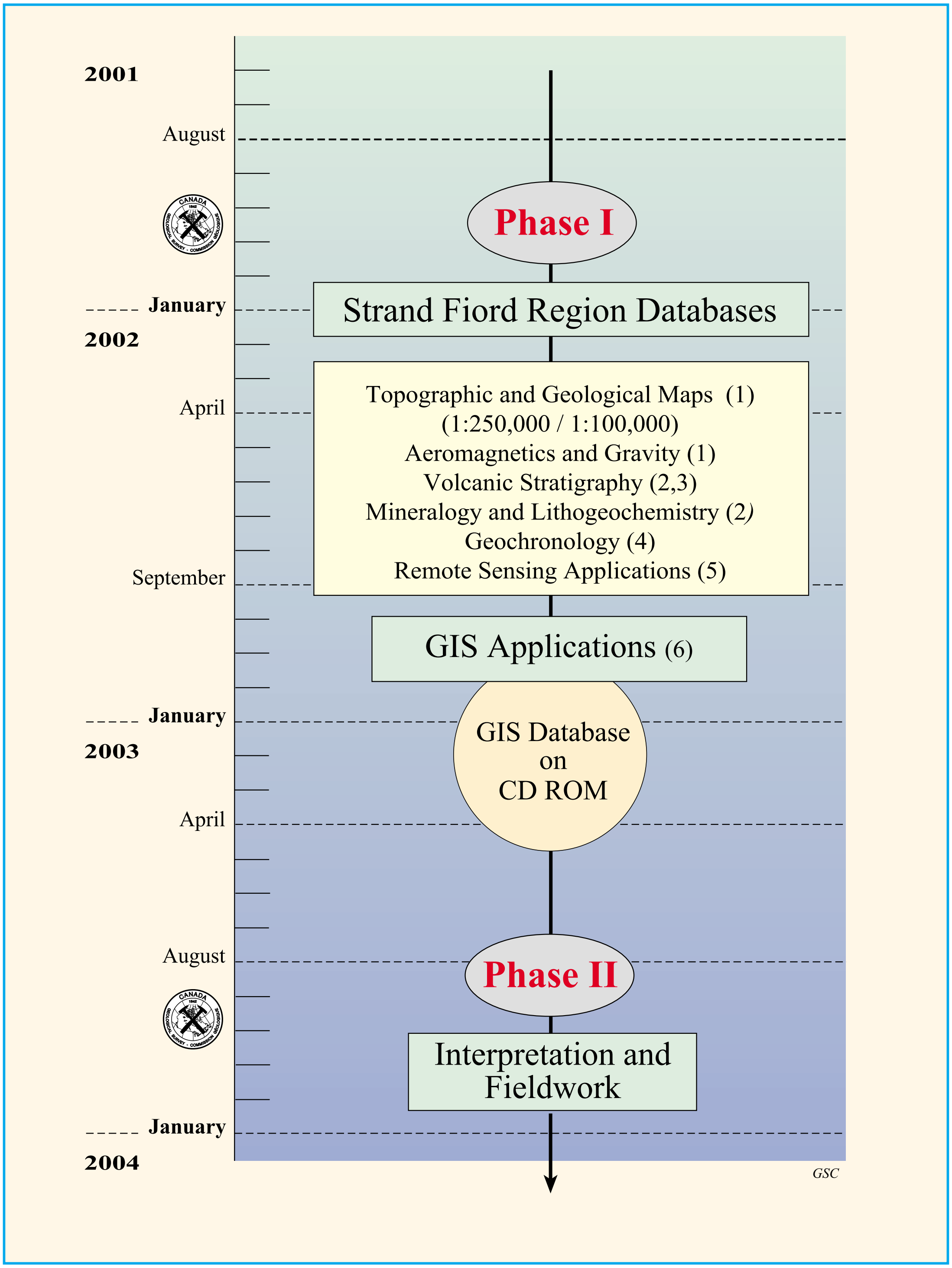


Figure 11. Flow chart illustrating the timetable, and deliverables of the project, in Phase I and Phase II. Numbers are keyed to project participants in Phase I :
(1) Gordon Oakey, GSC Atlantic; (2) Marie-Claude Williamson, Project leader, GSC Atlantic; (3) Andrew MacRae, GSC Atlantic; (4) Mike Villeneuve, GSC Ottawa; (5) Paul Budkewitsch, Canadian Centre for Remote Sensing; (6) Andrew Sherin, GSC Atlantic. The logo indicates the start of a yearly protocol leading to project review, approval, and funding at the Geological Survey of Canada, Natural Resources Canada.

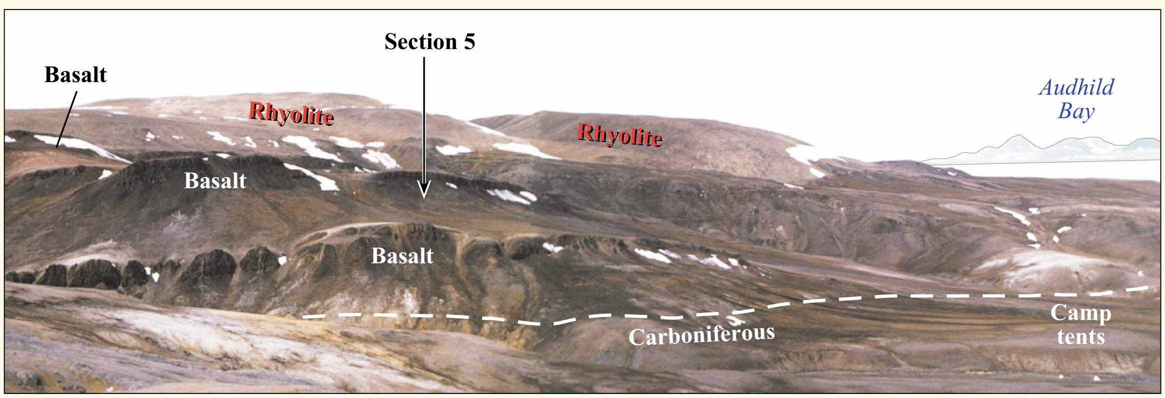
during Phase I. We also introduce a long-term view of the project that involves another region of the SBMP with the potential for hosting volcanic-hosted massive sulphide (VMS) deposits.

4. *PHASE II*: FIELD WORK IN THE STRAND FIORD REGION, AND ON NORTHERN ELLESMERE ISLAND

The most important objective of the project in *Phase II* is to groundtruth the interpretations obtained using the GIS database for the Strand Fiord region, as guided by exploration criteria for Ni-Cu-PGE deposits (Fig. 11). The results obtained from GIS database development, manipulation, and interpretation will facilitate a comparison between flood basalts and intrusives in the Strand Fiord region, and those hosting giant Ni-Cu-PGE deposits in the Noril'sk region, providing a decision support tool for mineral exploration is this area.

Another *Phase II* objective is to conduct field work and sampling of the Hansen Point Volcanics, on northern Ellesmere Island (Area 2, Fig. 3). Specific goals are to:

(1) fill the existing geoscience gaps in this region;
(2) initiate the production of a second GIS database applied to the search for volcanic-hosted massive sulphide (VMS) deposits.



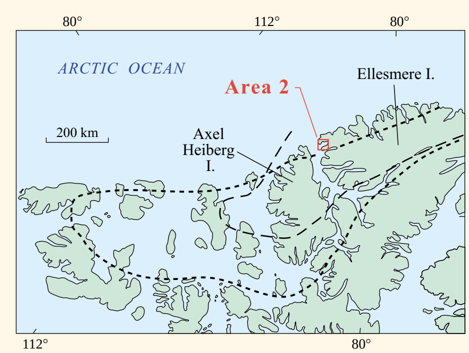


Figure 12. Wide angle view of the Hansen Point Volcanics, as observed in the area of Emma Fiord, on northern Ellesmere Island (Figs. 2 and 3). The traverse that corresponds to Section 5 (Fig. 13) is arrowed.

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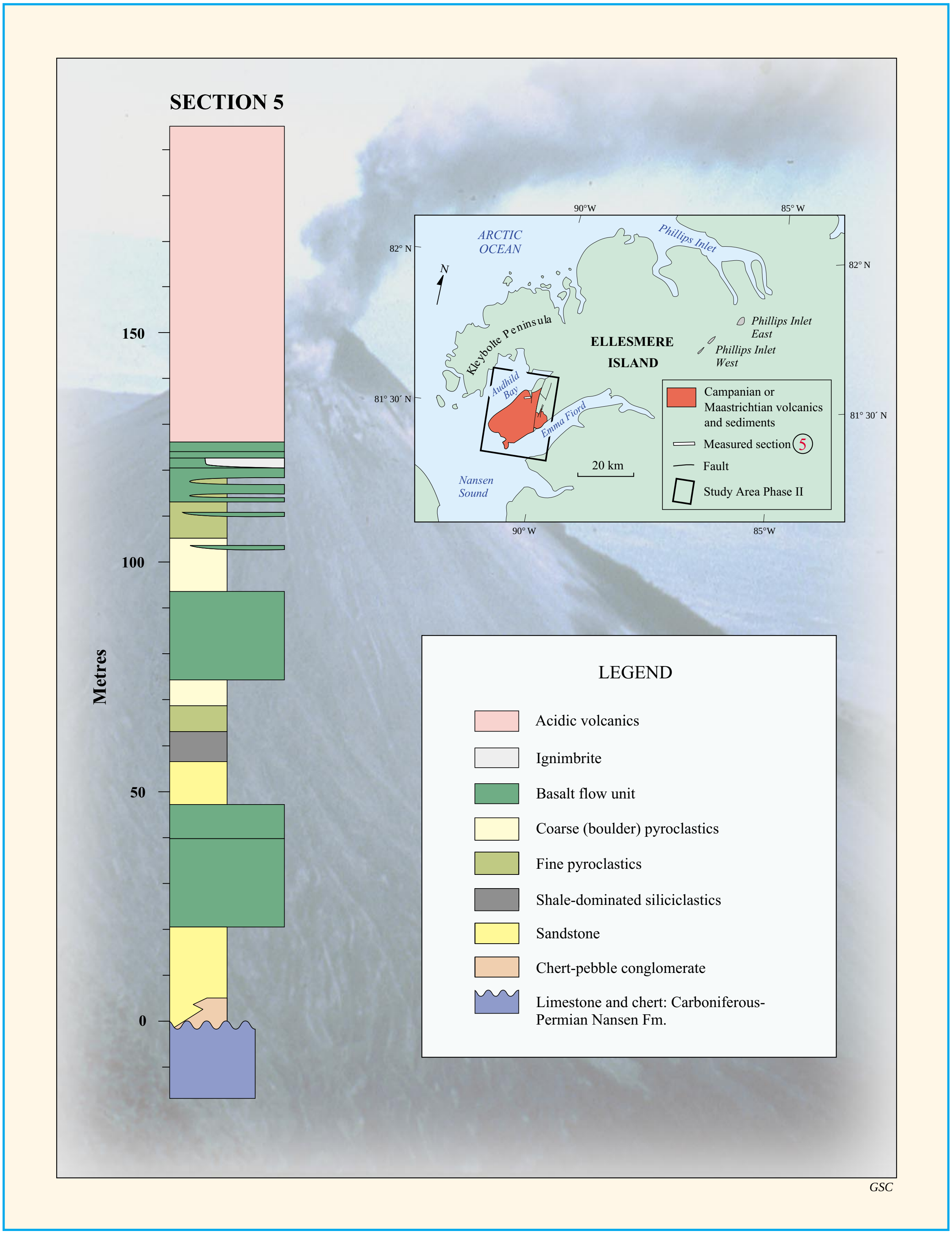

Figure 13. Schematic stratigraphic section of the Hansen Point Volcanics located in Area 2 of the proposed project (modified from MacRae, 1989).

The Hansen Point Volcanics (HPV) outcrop in two areas of northern Ellesmere Island (Fig. 2): at Emma Fiord, and near Yelverton Bay (Bates, 1986; MacRae, 1989; Merrett and Muecke, 1989). At both localities, the volcanic succession is bimodal, and silicic lava flows predominate. U-Pb age dates on volcanic rocks from the Yelverton Bay area are poorly constrained (Trettin and Parrish, 1987) but suggest a Late Cretaceous age. An age of 80 ± 1.7 Ma for samples of trachyte and rhyolite was recently obtained using Rb-Sr whole rock geochronology (S. Estrada, Pers. Comm. 2000).

Near Emma Fiord, pyroclastic flows and volcaniclastic rocks of the HPV are interlayered with mafic and silicic lava flows (Fig. 12; MacRae, 1989). The area has not yet been mapped at a scale of 1:250,000, however, stratigraphic data are available from the studies of Bates (1986) and MacRae (1989; Fig. 13).

Some of the features of the HPV are interesting from the point of view of VMS exploration:

- The volcanic stratigraphy suggests the presence of a remnant caldera, developed in an area of thickened continental crust (Meneley *et al.*, 1975).
- The volcanic system is adjacent to the geological boundary between the Sverdrup Basin and Pearya Terrane (Fig. 2), which may coincide with the trace of a major fault.
- The volcanic succession is adjacent to a circular, high-amplitude magnetic anomaly (G. Oakey, Pers. Comm., 2001).

The important factors to be considered in evaluating the mineralization potential of this region are *the extensional regime, the presence of pyroclastic rocks, and evidence for crustal melting*. The anomalous heat flow associated with crustal thinning, in combination with the availability of hydrothermal fluids, are critical factors in the generation of VMS deposits within thermally-driven, conductive systems (Swinden, 1996). The available age dates suggest that the HPV were erupted 15 Ma following the emplacement of flood basalts, during the waning stages of rift-related igneous activity (Muecke *et al*., 1990). The presence of Late Cretaceous bimodal intrusive rocks near Yelverton Bay suggests that shallow-level subvolcanic intrusions underlie the volcanic edifices, and could have provided the required heat source. Similarities with some aspects of the Bell River Complex, in the Superior Province (Galley, 1996), include the presence of Fe-Ti rich mafic magmas feeding the volcanic succession, and preliminary evidence for magmatic underplating and crustal melting (Williamson, 1998).

Field activities planned for the HPV at Emma Fiord would include mapping, rock sampling and geochemical analysis, age dating, and the eventual production of a GIS database constructed using the template defined in *Phase I*.

5. CONCLUSIONS

We describe a project under development by the Geological Survey of Canada, to investigate the potential for Ni-Cu-PGE deposits in flood basalts and associated intrusions of the Strand Fiord Formation, in the Canadian Arctic Islands. Many of the attributes of the igneous province compare favourably with those of flood basalts hosting giant deposits of this type in the Noril'sk region of northern Russia.

The document presents the planned objectives, deliverables and timetable of the project, and invites comments and suggestions from mining companies at the project development stage. The most important activity of the project in *Phase I* is to integrate several databases for the Strand Fiord region into a Geographic Information System (GIS), distributed to participating mining companies, government agencies, and project collaborators. Activities in *Phase II* of the project will include field work in the Strand Fiord region to groundtruth and calibrate the interpretations obtained during *Phase I*. In addition, mapping and data collection in the Emma Fiord region, northern Ellesmere Island, will investigate the potential for bimodal successions to contain volcanic-hosted massive sulphide (VMS) deposits.

The results obtained from the GIS database, interpretations, and subsequent field studies, will allow a comparison to be made between the flood basalt lavas and intrusions in the Strand Fiord region, and those hosting the Ni-Cu-PGE deposits in the Noril'sk region, providing a decision support tool for mineral exploration in this region. The proposed objectives and deliverables of the project under development are consistent with the Natural Resources Canada program plans for the Sustainable Development and Management of Natural Resources in the North.

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Source of background photographs :

Figure 5 : Kilauea, Hawaii, U.S. : This basaltic shield volcano on the Island of Hawaii is among the most extensively studied volcanoes in the world. Shown here is a lava fountain from the 1959 eruption of Kilauea Iki. Photograph credit : University of Colorado. No. 6 in *Volcanoes in Eruption, Set I*; National Geophysical Data Center, NOAA, U.S. Department of Commerce.

Figure 6 : View of Expedition Fiord taken from Dragon Mountain. Strand Fiord, western Axel Heiberg Island, Nunavut. Photograph by A. MacRae.

Figure 7 : Pacaya, Guatemala : Pacaya is a volcanic complex of two small strato-volcano cones and older lava domes in Southern Guatemala. It has erupted over twenty-two times since its birth in 1565, and nearly annually since 1965. Eruptions are generally characterized by explosions but recent eruptions have also produced lava flows. This view shows an ash eruption shortly after the February 4, 1976, magnitude 7.5 earthquake. Photograph credit : U.S. Geological Survey. No. 16 in *Volcanoes in Eruption, Set I*; National Geophysical Data Center, NOAA, U.S. Department of Commerce.