Current Research (2019) Newfoundland and Labrador Department of Natural Resources
Geological Survey, Report 19-1, pages 1-21

PETROGRAPHIC, GEOCHEMICAL AND SULPHUR ISOTOPE STUDIES OF GABBRO SILLS, LABRADOR TROUGH: IMPLICATIONS FOR Ni–Cu–PGE EXPLORATION

J. Conliffe, A. Smith[1] and D. Wilton[1]
Mineral Deposits Section
[1]Department of Earth Sciences, Memorial University of Newfoundland, St. John's, NL, A1B 3X5

ABSTRACT

Numerous documented Ni–Cu–PGE occurrences occur in the Hurst and Retty lithotectonic zones, part of the Labrador Trough in western Labrador and northeastern Québec. These occurrences are hosted in Paleoproterozoic mafic and ultramafic sills, which were intruded during rift-related magmatism, in an extensional environment, associated with the formation of pull-apart basins along the continental margin, prior to the New Québec Orogen.

In the summer of 2017, samples were collected from gabbro sills in the Howse Lake and the Moss Lake areas, western Labrador, as well as from the Huckleberry prospect in Québec (approximately 80 km to the north-northwest of Howse Lake). Samples were collected from aphyric and glomeroporphyritic gabbro sills as well as ultramafic sills. These have been subdivided into mineralized (> 5% sulphide minerals) and non-mineralized samples. This report presents petrographic descriptions of mineralization (including SEM-MLA analysis of sulphides and PGE-minerals), as well as whole-rock lithogeochemistry and sulphur isotope analysis.

Mineralization predominantly consists of variable proportions of pyrrhotite, chalcopyrite and pentlandite (± pyrite), occurring as disseminations, blebs, patches and rarely, net-textured sulphides. Metal contents are highly variable, and mineralized samples from the Howse Lake area contain up to 0.41% Cu, 621 ppm Ni and low PGE contents (Pt + Pd < 100 ppb), whereas strongly mineralized samples from the Huckleberry area contain up to 1.22% Cu, 0.20% Ni, and 436 ppb Pt + Pd. The SEM-MLA analysis has identified a number of discrete PGE minerals in samples from all areas, with a predominant Pd–Bi–Te composition.

In the Howse Lake area, sulphur isotope data is consistent with the addition of crustal sulphur via *assimilation of country rocks. High Cu/Pd ratios may be related to derivation under sulphur-saturated melting conditions, depletion of Pd* via *early sulphide segregation during the ascent of magmas or the bulk assimilation of host sedimentary rocks, which are commonly enriched in Cu. Samples from the Moss Lake area have Cu/Pd ratios close to mantle values and sulphur isotope data indicates sulphur was assimilated from the surrounding country rocks. In contrast, sulphur isotope data from mineralized gabbros from the Huckleberry area indicate a dominantly magmatic sulphur source, and the high Cu/Pd ratios must be a feature of the magmas, inherited from source melting or* via *depletion of the magma during earlier sulphide segregation.*

INTRODUCTION

Magmatic sulphide deposits form *via* the segregation of an immiscible sulphide liquid from a silicate magma. Because of enhanced elemental partition coefficients, the sulphide liquid will become relatively enriched in Ni, Cu, and PGEs compared to the silicate melt. These types of deposits are a major global source of Ni and PGE, also providing significant quantities of Cu and Co as by-products (*e.g.*, Barnes and Lightfoot, 2005; Naldrett, 2010).

In the Labrador Trough region of western Labrador and northeastern Québec, a series of rift-related mafic and ultramafic sills intrude sulphide-rich sedimentary rocks in different fault-bonded tectonic zones. Geologically, these gabbro sills exhibit many of the criteria suggested for potential hosts for magmatic Ni–Cu–PGE deposits (Barnes *et al.*, 2016). There are numerous Ni–Cu–PGE occurrences within the Labrador Trough (Clark and Wares, 2005), and significant base-metal and PGE values are recorded from several showings, including the Frederickson Lake, Huckleberry and the Lac Retty prospects.

In the summer of 2017, samples were collected from gabbro sills in the Howse Lake (NTS map area 23O/01) and Moss Lake areas (NTS map area 23I/08) (Figure 1). Samples were also collected from the Huckleberry prospect, located approximately 80 km to the north-northwest of Howse Lake in Québec (Figure 1). Recent exploration at the Huckleberry prospect identified significant Cu–Ni–PGE mineralization, with 98 grab samples having an average grade of 1.0% Cu, 0.2% Ni and 0.72 g/t PGE, with highs of 14% Cu, 1.2% Ni and 17g/t PGE + Au from individual grab samples (Vaillancourt *et al.*, 2016). The geological setting of gabbro sills in Labrador was described in detail by Smith *et al.* (2018), and whole-rock geochemical data from the Howse Lake and Moss Lake areas were published in Conliffe and Smith (2018). This report summarizes additional results of a recently completed B.Sc. thesis at Memorial University (Smith, 2018). In addition to petrographic studies, this project included whole-rock lithogeochemistry and sulphur isotope analyses. The results from all three study areas are compared, with the aim of determining common factors that contributed to mineralization.

REGIONAL SETTING

STRATIGRAPHY

The Labrador Trough, located in western Labrador and northeastern Québec, is composed of three cycles of Paleoproterozoic sedimentary and volcanic rocks collectively forming the Kaniapiskau Supergroup (Frarey and Duffell, 1964; Zajac, 1974; Wardle and Bailey, 1981; Le Gallais and Lavoie, 1982; Clark and Wares, 2005). Geochronological data imply that these cyclic sequences formed between 2.17 and 1.87 Ga (Rohon *et al.*, 1993; Findlay *et al.*, 1995; Machado *et al.*, 1997; Bleeker and Kamo, 2018).

Cycle 1 rocks consist of an intercratonic rift basin sequence (Seaward Formation) overlain by the passive margin sequence of the Swampy Bay and Attikamagen groups (Le Fer, Denault, Fleming and Dolly formations). Cycle 2 consists of two laterally equivalent sequences, the Ferriman Group in the west and the Doublet Group in the east. The Ferriman Group is a transgressive sequence that progresses from shelf-type rocks of the Wishart Formation (sandstone and siltstones) and the Sokoman Formation (iron formation) at the base, to deeper water turbidites (and minor basalts) of the Menihek Formation at the top. The intermediate to mafic volcanic rocks of the Nimish Formation are interbedded with the Sokoman Formation in the Dyke Lake area (Evans, 1978). The Doublet Group is interpreted to represent deeper water equivalents of the upper Ferriman Group (Clark and Wares, 2005), comprising pyroclastic rocks of the Murdoch Formation at the base, overlain by siltstones and black shales of the Thompson Lake Formation and basalts of the Willbob Formation. Locally, Cycle 2 is unconformably overlain by the Tamarak River Formation, which consists of arkosic rocks interpreted as a synorogenic foredeep molasse sequence (Cycle 3).

Throughout the central regions of the Labrador Trough, the rocks of Cycle 1 and Cycle 2 are intruded by mafic to ultramafic sills of tholeiitic affinity, which were traditionally grouped together as the Montagnais Group or the Montagnais sills (Frarey and Duffell, 1964; Baragar, 1967; Skulski *et al.*, 1993; Findlay *et al.*, 1995). However, geochronological constraints now indicate at least two discrete magmatic episodes (Rohon *et al.*, 1993; Findlay *et al.*, 1995; Bleeker and Kamo, 2018). Rohon *et al.* (1993) reported a U–Pb zircon age of 2196 ± 4 Ma from a felsic differentiate of a gabbro sill that intruded the Seward Group. Chemical abrasion ID-TIMS data from multiple, single-zircon grains, in a glomeroporphyritic gabbro sill that intruded the Menihek Formation, yield a concordant U–Pb age of 1878.5 ± 0.8 Ma (Bleeker and Kamo, 2018). The earlier phase of igneous activity is interpreted to have been associated with the initial rift phase of the Labrador Trough at ~2.2 Ga (Wardle and Bailey, 1981). The later phase of igneous activity may represent magmatism in pull-apart basins reflecting pre-collisional dextral transtension along the Superior margin (Skulski *et al.*, 1993). Recently, Bleeker and Kamo (2018) suggested that the later craton-scale Circum-Superior Belt magmatism was caused by hot mantle upwelling.

Bilodeau and Caron-Côté (2018) proposed that the term “Montagnais sills” be replaced, and that all mafic to ultramafic sills in the Labrador Trough be subdivided into two discrete suites based on the volcano-sedimentary sequence that they intrude, regardless of their age or interpreted origins. Mafic sills intruding Cycle 1 rocks (Seward, Swampy Bay and Attikamagen groups) were assigned to the Wakuach Intrusive Suite, and all mafic sills that intruded Cycle 2 rocks were grouped together with ultramafic sills in the Retty Lake area (formerly Retty Peridotite) into the Gerido Intrusive Suite.

Lithotectonic Zones

The Labrador Trough is divided into eleven lithotectonic zones, each with a characteristic stratigraphy and bounded by major thrust faults. Collectively, these terranes constitute an imbricated thrust stack, formed from thrusting during the final accretionary stages of the New Québec Orogen (Clarke and Wares, 2005).

All samples collected for this study are from within the Hurst and Retty lithotectonic zones. The Hurst Zone is composed of a thin sequence of Attikamagen Group sedimenta-

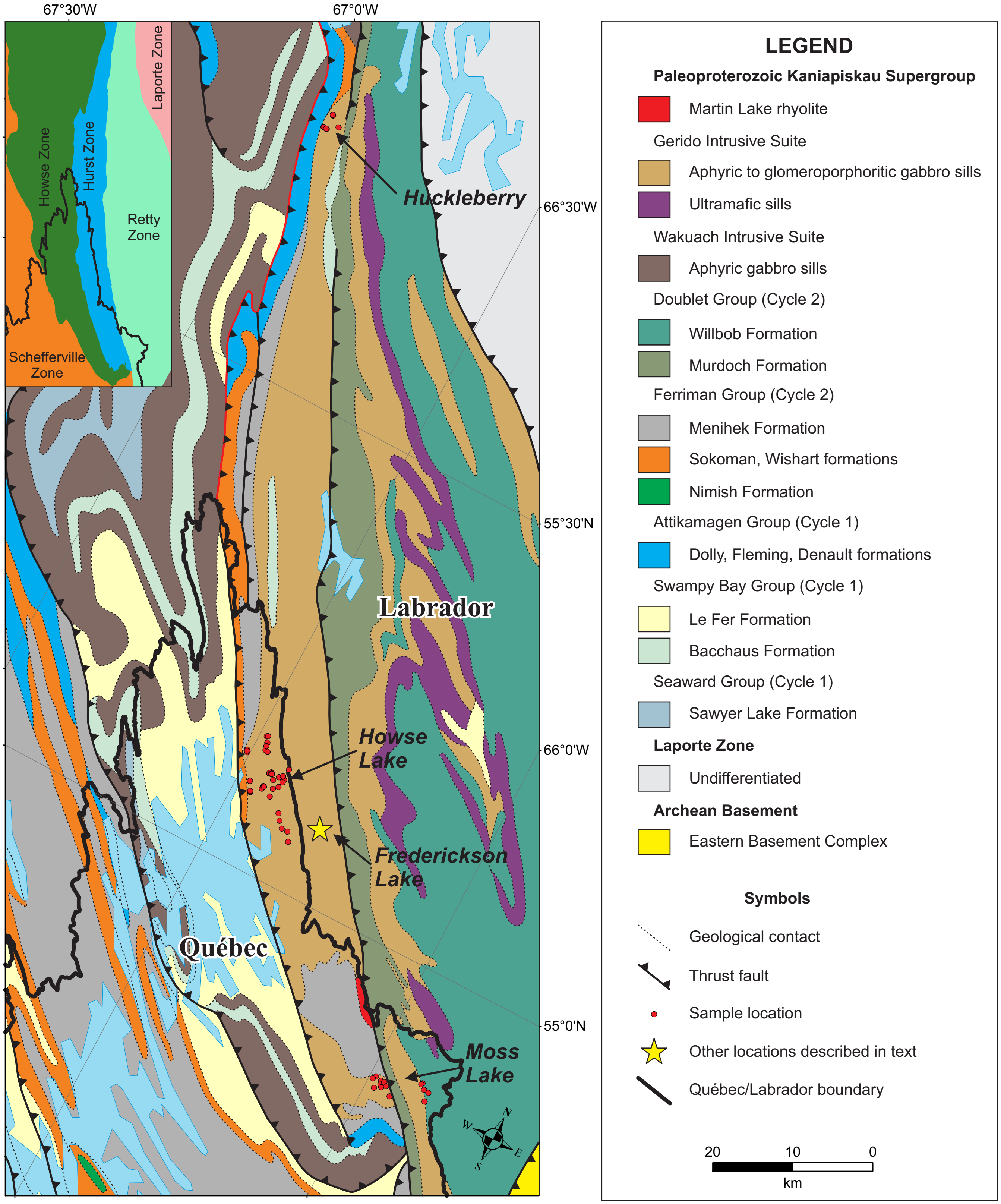

Figure 1. *Simplified geology map of the Labrador Trough in western Labrador and northeastern Québec, showing location of samples collected during 2017 fieldwork. Geology adapted from Wardle (1982) and Thériault and Beauséjour (2012). Inset map showing lithotectonic zones of the Labrador Trough (adapted from Clark and Wares, 2005).*

ry rocks overlain by the Ferriman Group. The Ferriman Group in the Hurst Zone consists primarily of Menihek Formation shales, siltstones and argillites, and it is host to numerous shale-hosted sulphide occurrences having elevated Cu contents (Swinden and Santaguida, 1993, 1994).The Menihek Formation is also intruded by numerous aphyric and glomeroporphyritic gabbro sills. The Retty Zone is bounded by the Walsh Lake Fault to the west, and is thrust over the Hurst Zone in the study area (Wardle *et al.*, 1990). The Retty Zone is composed of the Willbob, Thompson Lake and Murdoch formations of the Doublet Group, containing numerous mafic and ultramafic sills (Clark and Wares, 2005). Shales and siltstone of the Thompson Lake Formation correlate with the middle part of the Menihek Formation in the Hurst Zone (Findlay *et al.*, 1995; Clark and Wares, 2005).

PREVIOUS EXPLORATION

Although the potential of the Montagnais Gabbro sills to host Ni–PGE mineralization was noted by Bloomer (1955), subsequent exploration by Labrador Mining and Exploration focused on shale-hosted sulphide occurrences in the Menihek Formation. In 1989, Cliff Resources Corp. and Canaustra Gold Exploration Ltd. investigated the Montagnais Gabbro in the Howse Lake area for base-metal, PGE, and Au deposits (Findlay and Fowler, 1989). Although sulphide-rich zones were described, the potential for economic deposits of precious-metal mineralization was considered to be poor based on the low Ni, Cu and PGE assays (Findlay and Fowler, 1989; Findlay *et al.*, 1990). In 1992 Falconbridge Ltd. explored the Moss Lake area. Prospecting and lithogeochemical surveys were conducted to investigate the Montagnais Gabbro for Ni–Cu occurrences, and anomalous results included assay values of up to 0.98% Cu in coarse-grained gabbro (Butler and McLean, 1992).

Several Ni–Cu–PGE occurrences are reported from Montagnais Gabbro sills in Québec (Clark and Wares, 2005). Although most of these occurrences are considered to be minor, significant base-metal and PGE values are recorded from a few showings, including the Frederickson Lake and Huckleberry showings in the Hurst Zone. Prospecting activity at Frederickson Lake, located ~12 km southeast of the Howse Lake area, reported grades of up to 3.99% Cu, 1.03% Ni and 0.69 g/t Pt + Pd from grab samples of mineralized gabbro (Scott *et al.*, 1988). The Huckleberry showing has been the focus of recent exploration by Northern Shield Resources, including prospecting and diamond drilling. Ninety-eight grab samples of mineralized glomeroporphyritic and olivine-bearing gabbros returned average grades of 1.0% Cu, 0.2% Ni and 0.72 g/t PGE, with highs of 14% Cu, 1.2% Ni and 17g/t PGE + Au from individual grab samples (Vaillancourt *et al.*, 2016).

GEOLOGY AND PETROGRAPHY

All gabbro sills examined during this study intrude Cycle 2 shales and siltstones of the Menihek Formation, Ferriman Group (Hurst Zone), and the Thompson Lake Formation, Doublet Group (Retty Zone), and are therefore part of the Gerido Intrusive Suite (Bilodeau and Caron-Côté, 2018). The sills generally range in thickness from <100 to 500 m (Findlay, 1996), but increase to ~2000 m in the Huckleberry area (Vaillancourt *et al.*, 2016). They typically exhibit some degree of differentiation, exhibited as rhythmic layering, cumulate oxide horizons, or variations in phenocryst abundance (Findlay, 1996). The sills have well developed chilled margins (Plate 1A). The presence of large aggregates of plagioclase crystal (glomerocrysts) is a characteristic feature of the gabbro, the abundance of glomerocrysts defines two main variants, namely aphyric gabbro and glomeroporphyritic gabbro (Baragar, 1967; Findlay, 1996).

Aphyric gabbro is the volumetrically most abundant rock type, comprising fine- to medium-grained, aphyric to sparsely glomeroporphyritic gabbro with <10% glomerocrysts by area (Plate 1B). The gabbro consists predominantly of sub- to euhedral plagioclase and augite, lesser amounts of orthopyroxene and hornblende, and minor Fe–Ti oxides and sulphides. Olivine is rare, and, where present, is commonly altered to serpentine, chlorite and Fe–Ti oxides. Aphyric gabbros typically have ophitic to subophitic textures (Plate 2A, B). Mesocumulate textures have also been recorded in some gabbros.

Glomeroporphyritic gabbro contains >20% plagioclase glomerocrysts, and is generally located in sill centres with gradational contacts through the enclosing aphyric gabbro (Findlay, 1996). The glomerocrysts are commonly irregularly shaped and 1–5 cm in diameter (Plate 1C), but large spherical glomerocrysts >10 cm in diameter have been recorded (Plate 1D). The glomerocrysts consist of numerous subhedral to euhedral, equant plagioclase crystals with interstitial plagioclase, and minor augite and Fe–Ti oxides. Sericitization and saussuritization is common, particularly in the cores of the glomerocrysts (Plate 2C). The outer rim of the glomerocrysts is commonly embayed and displays resorption textures, and an outer rim of more sodic plagioclase occurs on some glomerocrysts (Plate 2C). The groundmass between glomerocrysts is similar to that of the aphyric gabbro, consisting of plagioclase, augite, hornblende, orthopyroxene, Fe–Ti oxides and sulphides. Plagioclase crystals in the groundmass typically do not display the same degree of alteration as those in the glomerocryts.

Findlay (1996) noted that plagioclase crystals in the groundmass were orientated in a concentric pattern around the glomerocrysts, and in conjuction with the resorption tex-

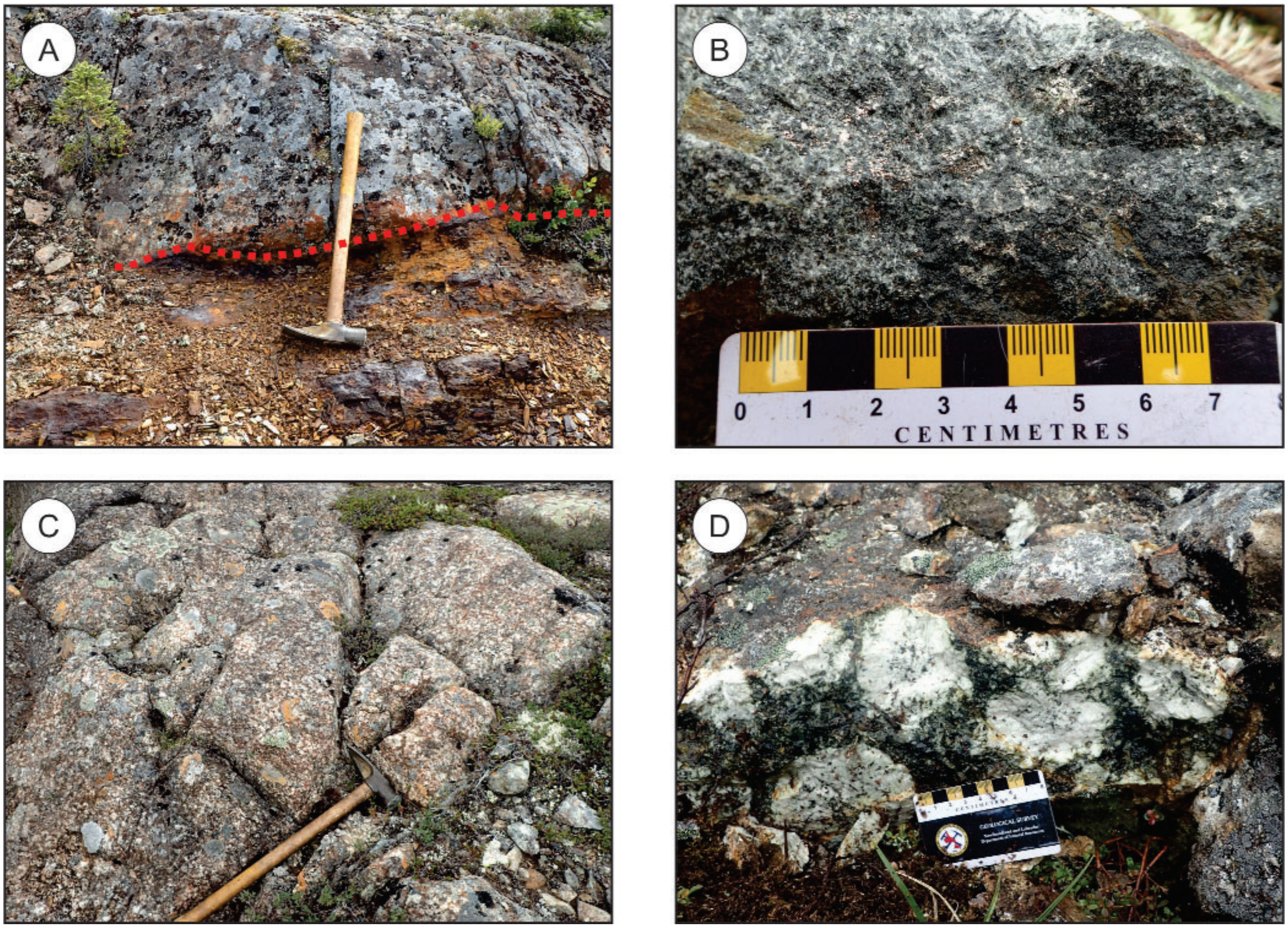

Plate 1. *Selected photographs from 2017 fieldwork. A) Contact between sulphide-rich Menihek Formation sediments (bottom) and chilled margin of gabbro sill, from the Howse Lake area; B) Aphyric gabbro in the Howse Lake area, with abundant disseminated sulphides; C) Outcrop of glomeroporphyritic gabbro in the Howse Lake area, with ~40% plagioclase glomerocrysts; D) Glomeroporphyritic gabbro from the Huckleberry area, with large (up to 10 cm) round 'snowball' plagioclase glomerocrysts.*

tures and sodic rims. Such observations indicate that the glomerocrysts formed prior to crystallization of the groundmass (possibly as flotation cumulates in a feeder magma chamber) and subsequently entrained in the magma during injection of the gabbro sills (Findlay, 1996).

Ultramafic rocks are recorded from the Huckleberry area, where olivine websterite and peridotite sills crosscut earlier aphyric and glomeroporphyritic gabbro (Vaillancourt *et al.*, 2016). These ultramafic units consist predominantly of pyroxenes (augite and orthopyroxene), hornblende and olivine (commonly altered to chlorite, epidote and Fe–Ti oxides), with numerous, highly irregular, plagioclase glomerocrysts having highly embayed margins, which likely became entrained in the magma. A possible olivine gabbro sill was also observed in the Howse Lake area, where a glomeroporphyritic gabbro with >50% glomerocryts was intruded by a Fe–Ti oxide-rich gabbro with numerous epidote veins. Petrographic examination of this magnetite-rich gabbro shows that magnetite pseudomorphs olivine (Plate 2D), and this may represent a strongly altered olivine gabbro.

Sulphide Mineralization

Sulphide mineralization occurs in aphyric gabbro, glomeroporphyritic gabbro and olivine websterite. Visual estimation of sulphide content ranges from <1% in disseminated mineralization, up to 15–20% sulphides in the most highly mineralized samples. The abundance of sulphide varies between the three study areas; samples from the Huckleberry area have the highest percentage of sulphides (commonly >10%) and samples from the Moss Lake area containing only traces of sulphides (<2%).

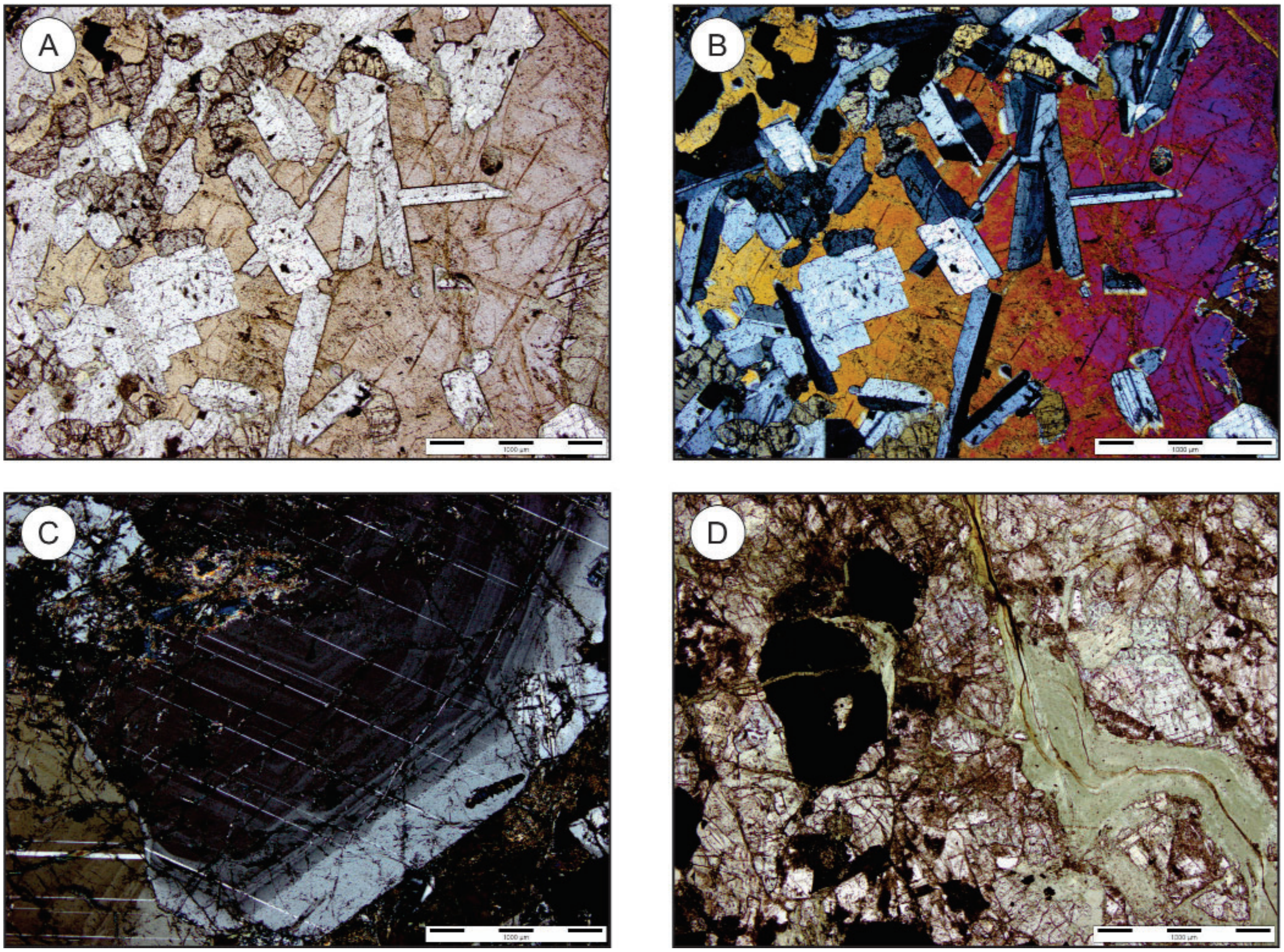

Plate 2. *Photomicrographs of gabbro samples. A) Poikilitic texture in gabbro from the Howse Lake area, with euhedral plagioclase in clinopyroxene oikocryst (plane-polarized light, sample 17JC034A02); B) Same view as A, in cross-polarized light; C) Plagioclase glomerocryts in glomeroporphyritic gabbro from the Howse Lake area, showing more sodic rim, embayed edge due to resorption and altered centre of glomerocryt with plagioclase replaced by sericite (cross-polarized light, sample 17JC063A01); D) Fe–Ti oxide-rich gabbro from the Howse Lake area, with magnetite pseudomorphing olivine and epidote veinlet (cross-polarized light, sample 17JC038B01).*

Mineralization consists of various proportions of pyrrhotite, chalcopyrite and pentlandite (± pyrite). Pyrrhotite is the dominant sulphide (Plate 3A), with chalcopyrite located on the margins of pyrrhotite grains (Plate 3B) or as discrete grains and fine disseminations in the silicate phase. Pentlandite is observed as both exsolution from pyrrhotite and as blebs within sulphide aggregates (Plate 3C). In aphyric gabbro sills, the sulphides occur as disseminations, blebs and patches (Plate 3A). Locally, the patches form net-textures in the most highly mineralized samples. Glomeroporphyritic gabbros contain sulphide mineralization within the groundmass interstitial to the plagioclase glomerocrysts, with some samples from the Huckleberry area containing >50% sulphides in the interstitial groundmass (Plate 3D). Ultramafic samples from the Huckleberry area contain 2–5% finely disseminated sulphides.

In the Howse Lake area, sulphide droplets were observed in the chilled margin of a gabbro dyke, <5 m from the contact with sulphide-rich sedimentary host rocks. These droplets are rounded and up to 5 mm in diameter. They consist primarily of pyrrhotite, have a cap of chalcopyrite and medium-grained silicate minerals (Plate 3E), and are interpreted to represent remnants of sulphide melt and vapour bubbles, which were frozen in the chilled margins of the sills and which may be related to assimilation of sulphide-rich country rocks (Barnes *et al.*, 2017).

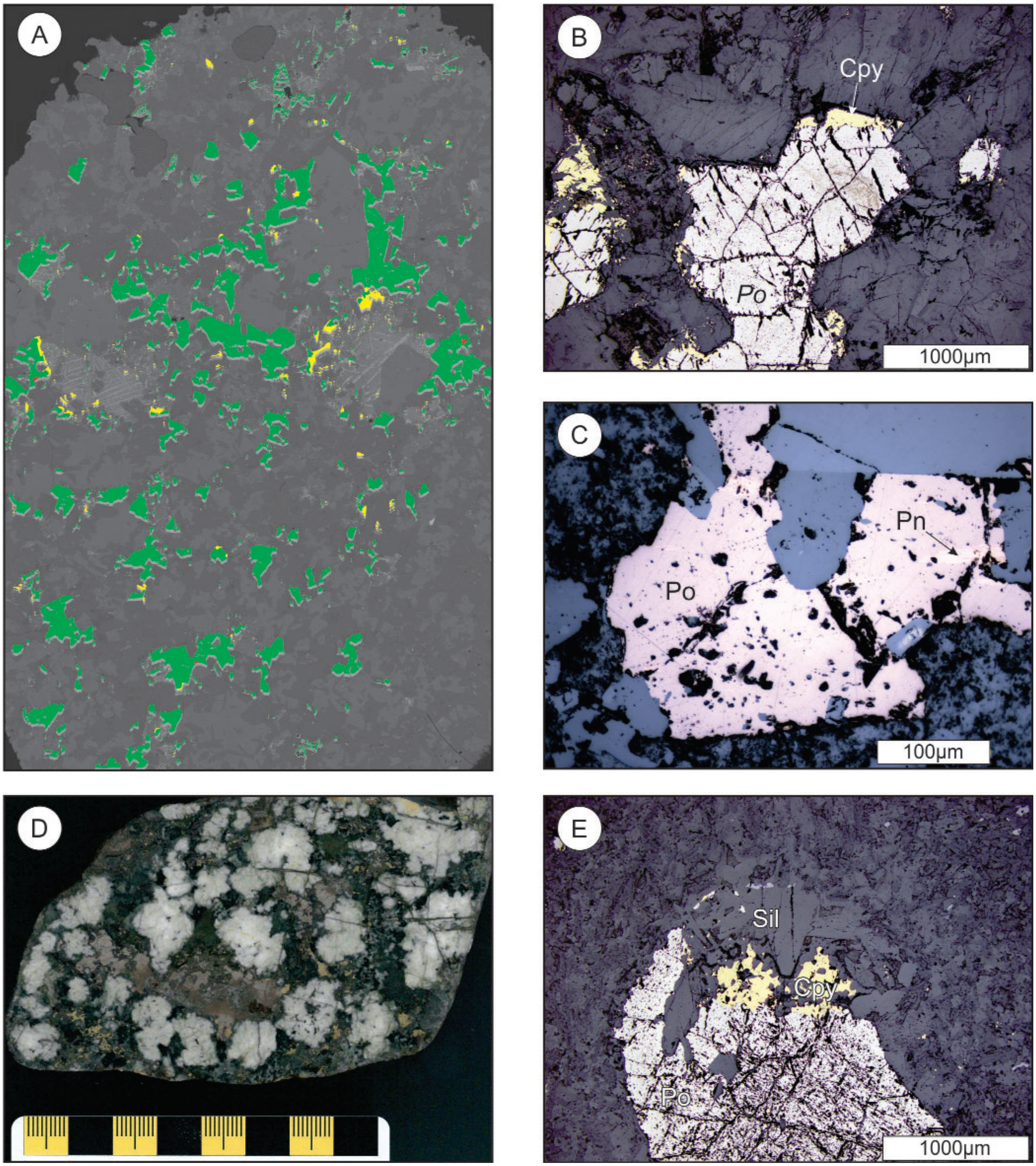

Plate 3. *A) Composite image of SEM-MLA false colour map and BSE image of aphyric gabbro from the Howse Lake area (sample 17JC034A02) with disseminated to patchy pyrrhotite (green), chalcopyrite (yellow) and minor pentlandite (red); B) Bleb of pyrrhotite (Po) with rim of chalcopyrite (cpy) (reflected light, sample 17JC034A01); C) Interstitial pyrrhotite (Po) with minor pentlandite (Pn) from groundmass of glomeroporphyritic gabbro in the Moss Lake area; D) Mineralized glomeroporphyritic gabbro from the Huckleberry area (sample 17JC091A02), with abundant pyrrhotite and chalcopyrite interstitial to glomerocrysts; E) Sulphide droplet from chilled margin of gabbro sill, with dominant pyrrhotite (Po) composition and cap of chalcopyrite (cpy) and silicates (Sil).*

Platinum Group (PGE) Minerals

Discrete PGE minerals in gabbro and olivine websterite samples from the Howse Lake, Huckleberry and Moss Lake areas were identified during SEM-MLA analysis. Individual PGE mineral grains vary in size from 1 to 11 µm across, and occur as either round equant grains, or irregular and lath-shaped grains. The PGE minerals occur within and along the margins of pyrrhotite, pentlandite, and rarely chalcopyrite grains (Plate 4A, B). The elements present in PGE minerals were determined using energy dispersive X-ray (EDX) spectrometry during EM-MLA analysis, which is capable of determining the chemical composition of the mineral rather than directly identifying the mineral phase. The Pd-bearing PGE minerals are the most common type identified, with the majority of PGE minerals having a chemical composition of Pd–Bi–Te. The Pt-bearing PGE minerals are rare, with a single Pt–Pd–Bi–Te mineral observed in one sample from the Huckleberry area. The PGE minerals with the chemical composition Pd–Ag–Pb–Te and Pd–Te–Se were recorded in a single sample from the Moss Lake area, whereas three Pd–Hg–Te minerals were recorded in a sample from the Howse Lake area.

GEOCHEMISTRY

Geochemical data were collected from 63 samples of sulphide-bearing, mafic and ultramafic units, with 41 from the Howse Lake area, 10 from the Moss Lake area and 12 from the Huckleberry area. Sample descriptions and UTM coordinates of samples from the Howse Lake and Moss Lake area are given in Conliffe and Smith (2018), and the locations of the samples are shown in Figure 1.

ANALYTICAL METHODS

All samples selected for geochemical analysis were prepared at the GSNL geochemistry laboratory in St. John’s. Major-element compositions (plus Cr, Zr, Be, Sc and Ba) were analyzed by ICP-OES methods, following lithium tetraborate and metaborate fusion. The REE and selected trace elements were determined by ICP-MS analysis following an identical sample digestion procedure, whereas other trace elements (As, Cd, Co, Cu, Li, Ni, Pb, Rb, V, Zn) were analyzed by ICP-MS after total acid digestion. The Loss-on-Ignition (LOI) was calculated after heating the sample to 1000°C. The Pd, Pt and Au contents were analyzed at Actlabs using the protocol outlined in Conliffe and Smith (2018). Analytical duplicates were inserted at a frequency of one in 20, with the duplicate selected at random. In addition, a selection of reference standards was analyzed, also at a frequency of one in 20. Full geochemical data and methods are outlined in Conliffe and Smith (2018).

Major- and Trace-Element Contents

Major-element and trace-element data indicate very little variation in gabbro composition between the three study areas. The samples have been subdivided based on the rock type (aphyric gabbro, glomeroporphyritic gabbro, olivine websterite or Fe–Ti oxide-rich gabbro) and the degree of mineralization (non-mineralized with <5% visible sulphides and mineralized with >5% visible sulphides). Selected major- and trace-element geochemical data are summarized in Table 1.

The major-element contents of aphyric and glomeroporphyritic gabbros are similar (Figure 2), where Al_2O_3 is

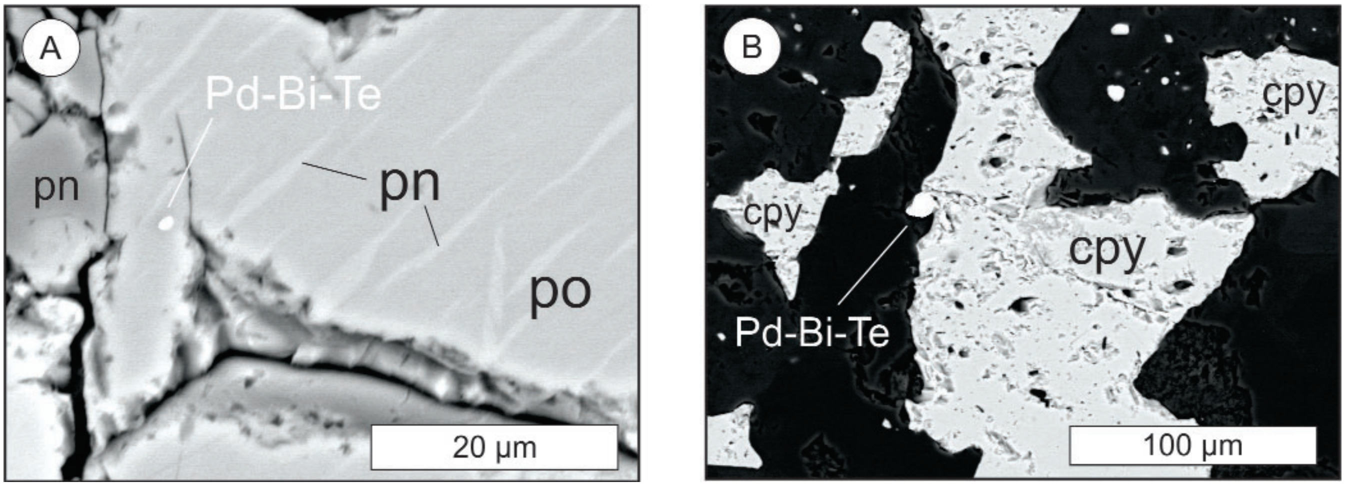

Plate 4. *A) Pd–Bi–Te PGE mineral in pyrrhotite with extensive pentlandite exsolution in the Howse Lake area (SEM backscatter image, sample 17JC100A02); B) Pd–Bi–Te PGE mineral on margin of chalcopyrite (cpy) grain from the Moss Lake area (SEM backscatter image, sample 17JC088A02).*

Table 1. Summary of lithogeochemical data from major rock types, showing average values (Av.) and standard deviations (St.Dev.). All oxides are given in wt. %, trace elements in ppm and Pd, Pt and Au in ppb. FeOT – total iron as ferrous iron; Mg# – [molecular MgO/(MgO+FeOT)]*100; dl – concentration is below detection limit. Full analytical data for samples from the Howse Lake and Moss Lake areas, including standards and duplicates, are given in Conliffe and Smith (2018)

	Aphyric Gabbro				**Glomeroporphyritic Gabbro**				**Olivine Websterite**		**Fe–Ti Oxide**
	Non-mineralized		**Mineralized**		**Non-mineralized**		**Mineralized**		**Mineralized**		**Gabbro**
n	**29**		**13**		**13**		**7**		**2**		**1**
	Av.	**St.Dev.**	**Av.**	**St.Dev.**	**Av.**	**St.Dev.**	**Av.**	**St.Dev.**	**Av.**	**St.Dev.**	
SiO_2	48.23	1.20	45.02	2.42	47.06	0.70	45.06	1.86	41.32	0.14	41.50
Al_2O_3	15.40	2.54	14.89	2.22	21.95	1.98	19.24	1.18	8.40	1.67	11.89
Fe_2O_3T	11.52	2.30	15.55	4.34	7.72	1.59	11.69	2.01	16.18	0.07	22.69
FeOT	10.36	2.07	14.00	3.91	6.95	1.43	10.51	1.81	14.56	0.06	20.41
Fe_2O_3	1.65	0.58	1.67	1.17	1.47	0.42	1.26	0.39	3.94	-	7.88
FeO	8.78	1.98	9.86	1.75	5.63	1.32	9.40	1.90	10.98	-	13.33
MgO	7.03	1.20	7.99	2.09	4.11	1.42	5.10	1.46	20.43	2.28	6.38
CaO	11.29	1.63	9.97	1.03	12.07	1.64	11.59	0.47	4.83	0.42	10.73
Na_2O	2.10	0.77	1.74	0.48	2.60	0.63	1.95	0.33	0.28	0.02	1.57
K_2O	0.35	0.28	0.24	0.28	0.36	0.25	0.35	0.17	0.40	0.40	0.15
TiO_2	0.940	0.350	0.821	0.303	0.602	0.217	0.786	0.218	0.462	0.061	2.389
MnO	0.192	0.049	0.193	0.036	0.125	0.021	0.145	0.029	0.198	0.009	0.208
P_2O_5	0.069	0.027	0.056	0.027	0.048	0.020	0.051	0.029	0.036	0.013	0.039
LOI	2.31	0.83	2.78	1.00	2.72	0.73	2.77	0.91	5.94	0.79	1.91
Total	99.42	0.73	99.26	0.71	99.36	0.94	98.72	0.69	98.47	0.42	99.44
Mg#	54.83	5.80	50.52	10.84	50.52	5.14	45.94	11.12	71.34	2.37	35.77
Cr	185	148	281	130	81	64	131	41	599	566	6
Ba	77	94	89	191	82	64	75	35	15	2	35
Sc	39	8	33	9	22	5	24	5	21	1	55
Zr	49	17	44	17	33	14	42	22	34	10	36
As	2	3	4	5	2	3	1	0	dl	dl	dl
Cd	0	0	0	0	0	0	0	0	0	0	0
Co	48	11	115	61	30	10	86	37	160	25	77
Cu	152	131	1746	1087	132	121	4777	4823	3441	1752	462
Li	14	8	11	6	12	8	14	8	10	9	8
Ni	88	43	391	177	60	43	821	703	1435	435	77
Pb	16	15	25	44	dl	dl	35	35	4	4	dl
Rb	13	11	10	8	13	11	15	8	29	29	12
V	295	92	265	82	177	63	262	54	160	18	1676
Zn	80	45	77	13	64	46	90	34	119	38	70
Ga	15	2	14	2	17	2	16	1	7	1	17
Ge	1.5	0.4	1.4	0.3	1.3	0.3	1.3	0.2	1.4	0.1	dl
Sr	120	39	105	23	187	44	184	27	30	2	97
Y	15	5	13	6	10	4	12	4	8	1	12
Nb	3	1	2	1	2	0	2	1	2	-	2
La	2.8	1.5	2.2	1.1	2.3	1.3	2.2	1.5	dl	dl	1.5
Ce	7.3	2.6	6.1	2.6	4.7	2.2	5.9	2.4	3.4	0.2	4.6
Pr	1.2	0.4	1.0	0.4	0.8	0.3	1.0	0.4	0.6	0.0	0.8
Nd	6.0	2.1	5.1	2.3	3.9	1.6	4.8	1.9	3.0	0.1	4.5
Sm	2.0	0.7	1.6	0.7	1.2	0.5	1.5	0.6	1.1	0.2	1.4
Eu	0.8	0.3	0.7	0.3	0.6	0.1	0.6	0.2	0.4	0.0	0.6
Tb	0.5	0.2	0.4	0.2	0.3	0.1	0.4	0.1	0.3	0.0	0.4
Gd	2.6	0.9	2.3	1.1	1.8	0.7	2.1	0.9	1.5	0.2	2.1
Dy	3.1	1.0	2.6	1.1	2.0	0.7	2.4	0.9	1.7	0.2	2.3
Ho	0.6	0.2	0.5	0.2	0.4	0.2	0.5	0.2	0.3	0.0	0.5
Er	1.9	0.6	1.7	0.8	1.3	0.5	1.5	0.5	1.0	0.1	1.6
Tm	0.3	0.1	0.2	0.1	0.2	0.1	0.2	0.1	0.1	0.0	0.2
Yb	1.8	0.6	1.5	0.7	1.1	0.4	1.4	0.5	1.0	0.1	1.5
Lu	0.3	0.1	0.2	0.1	0.2	0.1	0.2	0.1	0.2	0.0	0.2
Hf	1.3	0.5	1.1	0.5	0.8	0.4	1.1	0.7	0.8	0.1	1.1
Th	0.2	0.1	0.2	0.1	0.2	0.1	0.2	0.1	0.1	-	dl
U	0.1	0.0	0.2	-	0.1	0.0	dl	dl	dl	dl	dl
Pd	14	19	28	28	7	5	128	137	209	49	dl
Pt	11	12	17	10	4	2	44	46	61	17	dl
Au	5	3	13	7	3	1	19	12	35	7	dl

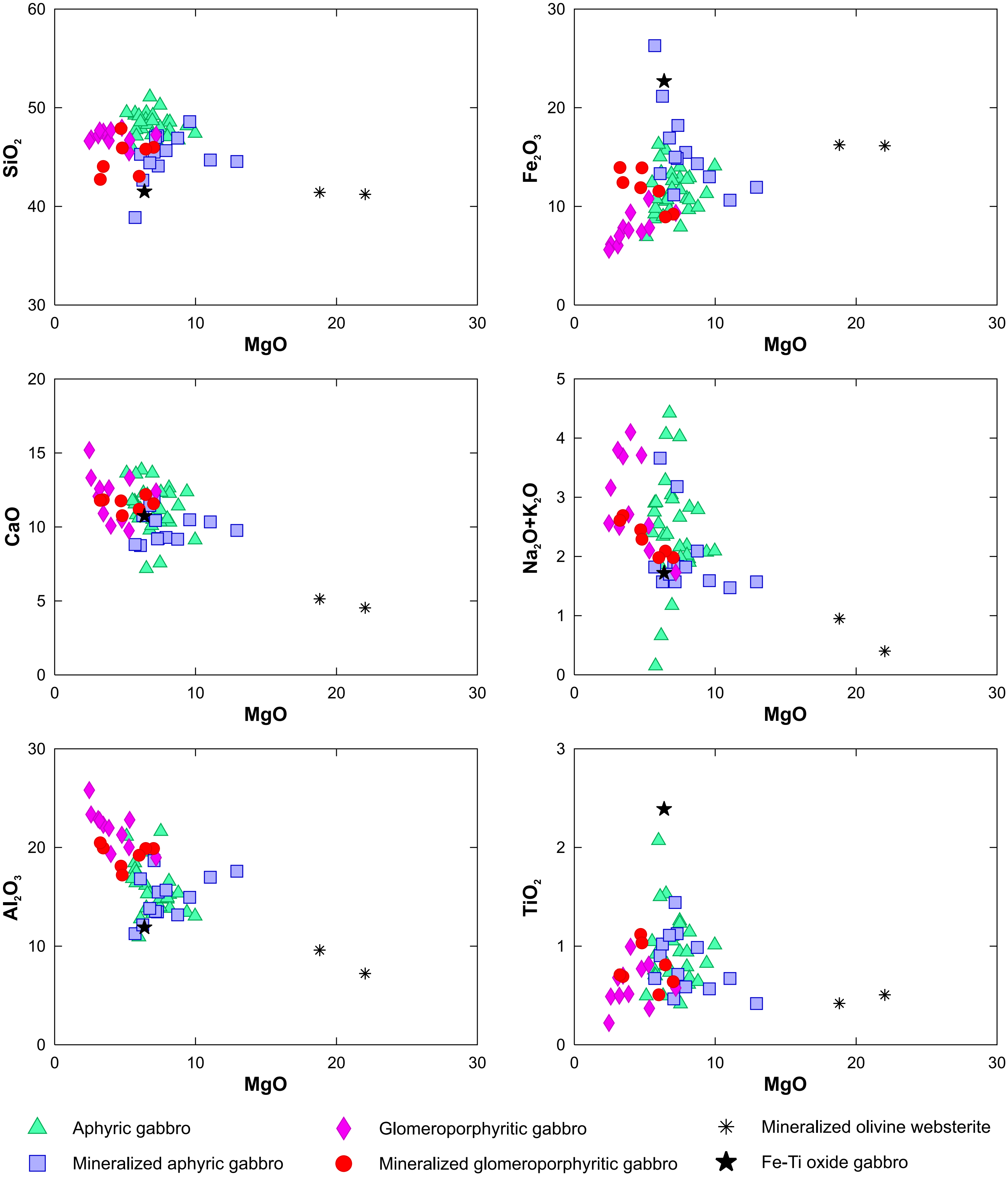

Figure 2. *Major-element oxide* vs. *MgO plots for mineralized and non-mineralized samples from the Howse Lake, Moss Lake and Huckleberry areas.*

elevated (due to higher plagioclase content) and MgO and Fe_2O_3 are slightly depleted in the glomeroporphyritic gabbros. Mineralized samples are characterized by higher Fe_2O_3 contents and associated lower contents of other major-element oxides, due to the dilution effect of the higher proportion of pyrrhotite. Two olivine websterite samples from the Huckleberry area are characterized by higher MgO contents and lower SiO_2, Al_2O_3, CaO and Na_2O contents (Figure 2). A single Fe–Ti oxide-rich gabbro sample from the Howse Lake area has high Fe_2O_3 and TiO_2 contents.

The concentration of REE and other trace elements are displayed on primitive mantle-normalized extended trace-element plots in Figure 3. These indicate that the various rock types are very similar in composition, and do not discriminate between mineralized and non-mineralized samples, indicating a common origin. With the exception of the large-ion lithophile elements (LILE) Rb and Ba, all samples have relatively flat profiles on the primitive–mantle normalized diagrams, and most trace-element compositions ranging from approximately 0.8 to 10 X primitive mantle. Some samples define slight depletions in Th and P. Chondrite-normalized REE multi-element diagrams show that all samples have flat REE profiles, with positive Eu anomalies in some samples (particularly in the glomeroporphyritic gabbros; Figure 4).

Immobile elements, including the high field-strength elements (HFSE) and REE, are preferred for lithogeochemical interpretations due to the variable alteration of the samples and the dilution effects created by sulphide mineralization. Based on the Zr/TiO_2 *vs.* Nb/Y discrimination diagram of Pearce (1996), all samples are classified as basaltic (Figure 5A). The Th/Yb *vs.* Zr/Y discrimination diagram of Ross and Bédard (2009) is used to determine the magmatic affinity of volcanic rocks, and for the samples from this study indicate a tholeiitic affinity (Figure 5B).

In Figure 5C, the samples are plotted on the Pearce (2008) Th–Nb crustal input plot, which uses the Th and Nb content as a proxy for crustal-derived geochemical variance (both these elements are immobile during weathering and behave similarly during most petrogenetic processes). With the exception of one mineralized aphyric gabbro sample, all samples plot within the more primitive MORB-OIB array (transitional between N-MORB and E-MORB) indicating minimal contamination by crustal assimilation.

Metal Content

Non-mineralized gabbro samples from all areas have low Cu and Ni contents (<572 and <183 ppm, respectively). Mineralized gabbro (aphyric and glomeroporphyritic) samples from the Howse Lake and Huckleberry areas are characterized by elevated Cu and Ni contents. With the exception for two strongly mineralized glomeroporphyritic gabbros from the Huckleberry area, Cu contents range from 381 to 4147 ppm and Ni contents from 95 to 621 ppm, with Cu/Ni ratios of 2.3 to 7.6. Two mineralized olivine websterite samples from the Huckleberry area contain 2202 to 4679 ppm Cu and 1128 to 1743 ppm Ni, with Cu/Ni ratios of 2 to 2.7.

All samples were also assayed for Pt, Pd and Au. Generally, contents of these metals were low (<100 ppb combined PGE + Au), with elevated values up to 464 ppb PGE + Au in strongly mineralized glomeroporphyritic gabbro and olivine websterite from the Huckleberry area. Samples from the Howse Lake and Moss Lake areas have highly variable Pd/Pt ratios (0.2 to 3.9). In comparison, samples from the Huckleberry area are consistently enriched in Pd compared to Pt (Pd/Pt ratios of 2.2 to 4.3).

The Cu/Pd ratio can be used to determine the conditions under which sulphides in magmatic systems formed (Barnes *et al.*, 1993). When a sulphide liquid segregates from a silicate magma, Pd partitions into the sulphide liquid with a partition coefficient ~1000 times greater than Cu. Therefore, if the sulphide liquid has equilibrated with a large volume of silicate magma (R-factor is >1000), Pd is enriched in the sulphide liquid and the Cu/Pd ratio will show an enrichment in Pd compared to normal mantle values (1000 to 10 000; Barnes *et al.*, 1993; Barnes and Lightfoot, 2005). If Cu/Pd ratios are greater than normal mantle values (*i.e.*, >10 000), Pd is depleted relative to Cu. Elevated Cu/Pd ratios may be related to derivation under sulphur-saturated melting conditions, or the depletion of Pd *via* early sulphide segregation during the ascent of magmas. In addition, it has been suggested that elevated Cu/Pd ratios may be useful as a prospecting tool, as depletion of Pd *via* early sulphide segregation may indicate that the sample may be located stratigraphically above or downstream from a potential deposit (Barnes *et al.*, 1993).

The Cu/Pd ratios of samples from the Howse Lake, Moss Lake and Huckleberry areas are shown in Figure 6. Samples from the Howse Lake and Huckleberry areas are generally depleted in Pd (Cu/Pd > mantle values), with some non-mineralized aphyric gabbros from the Howse Lake area plotting in the field expected for mantle values. In contrast, non-mineralized aphyric and glomeroporphyritic gabbros from the Moss Lake area generally plot in, or close to, the field expected for normal mantle values, indicating little fractionation of Cu and Pd.

IN-SITU SULPHUR ISOTOPE ANALYSIS

In-situ SIMS (Secondary Ion Mass Spectrometer) analysis of $\delta^{34}S$ ratios in pyrrhotite and chalcopyrite were

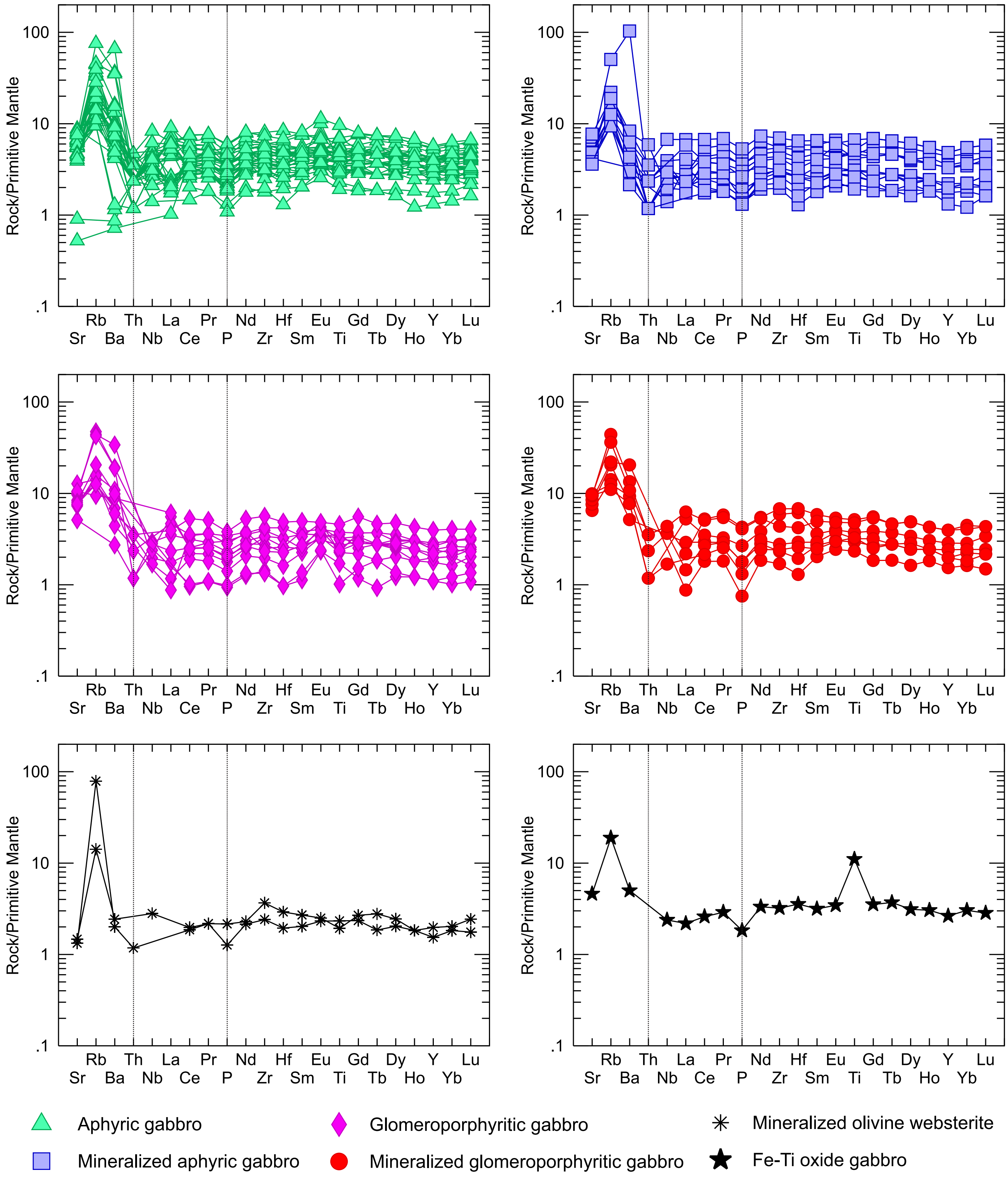

Figure 3. *Primitive mantle-normalized multi-element patterns for mineralized and non-mineralized samples from the Howse Lake, Moss Lake and Huckleberry areas (normalizing values from Sun and McDonough, 1989).*

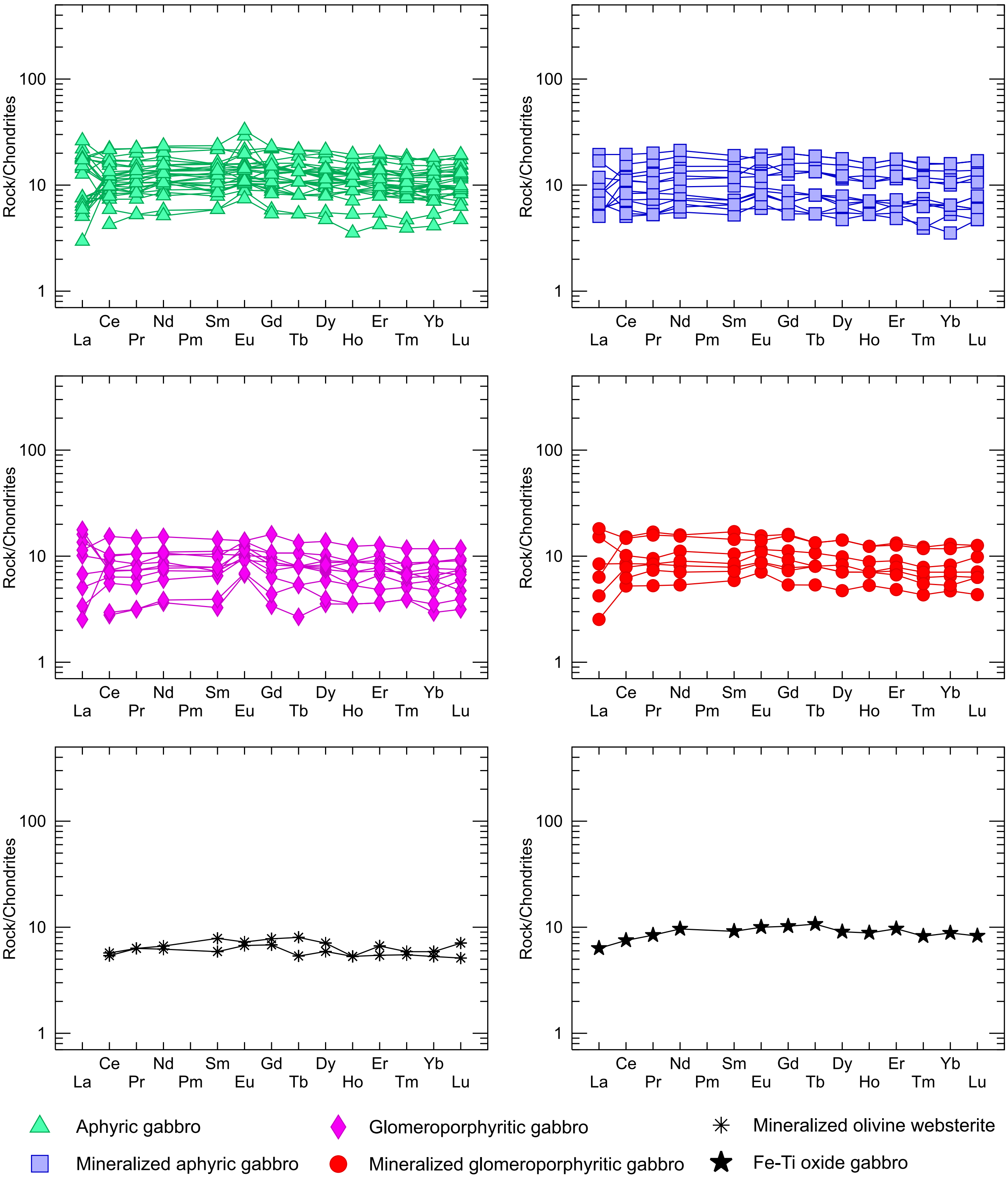

Figure 4. *Chondrite-normalized REE patterns for mineralized and non-mineralized samples from the Howse Lake, Moss Lake and Huckleberry areas (normalizing values from Sun and McDonough, 1989).*

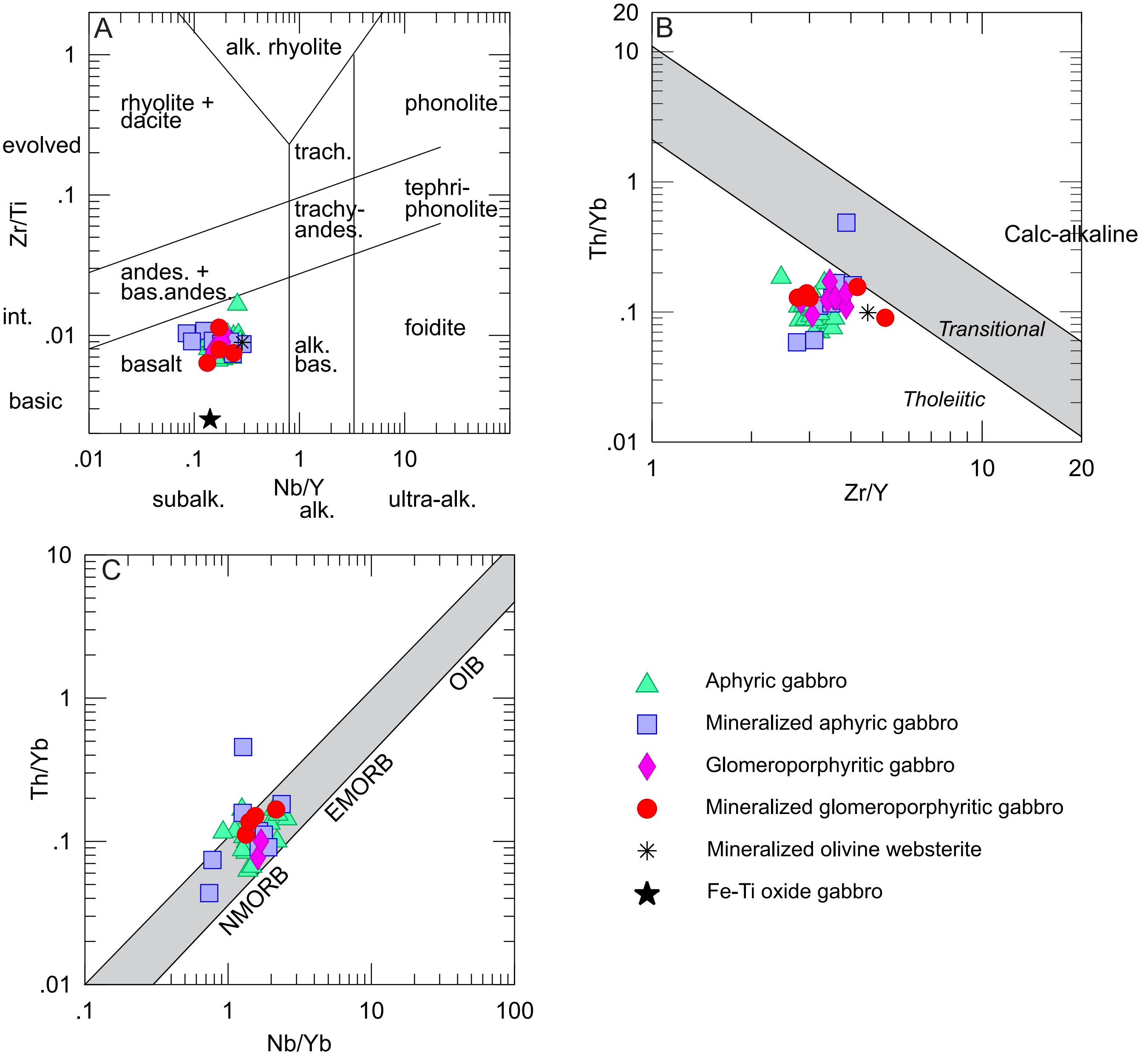

Figure 5. *Trace-element data for mineralized and non-mineralized samples plotted on selected discrimination diagrams. A) Zr/Ti* vs. *Nb/Y rock classification diagram (Pearce, 1996); B) Th/Yb* vs. *Zr/Y–discrimination diagram (Winchester and Floyd, 1977; modified by Ross and Bedard, 2009), showing tholeiitic, transitional and calc-alkaline fields; C) Th/Yb* vs. *Nb/Yb crustal input plot (after Pearce, 2008).*

performed on samples of gabbro and sulphide-rich shales from the Howse Lake, Moss Lake and Huckleberry areas, and are summarized in Table 2. Sulphur isotope data were obtained for sulphide minerals in five gabbro samples and one shale sample from the Howse Lake area (16 point analyses), two gabbro samples and one shale sample from the Moss Lake area (5 point analyses) and two gabbro samples and one shale sample from the Huckleberry area (18 point analyses). In total, 39 δ^{34}S spot analyses were obtained from two different minerals (chalcopyrite, n = 23; pyrrhotite, n = 16).

All analyses were performed at the SIMS laboratory, MAF-IIC Microanalysis Facility, Memorial University. Samples were mounted in polished epoxy sections and sputter coated with 300Å of Au prior to analysis by the Cameca

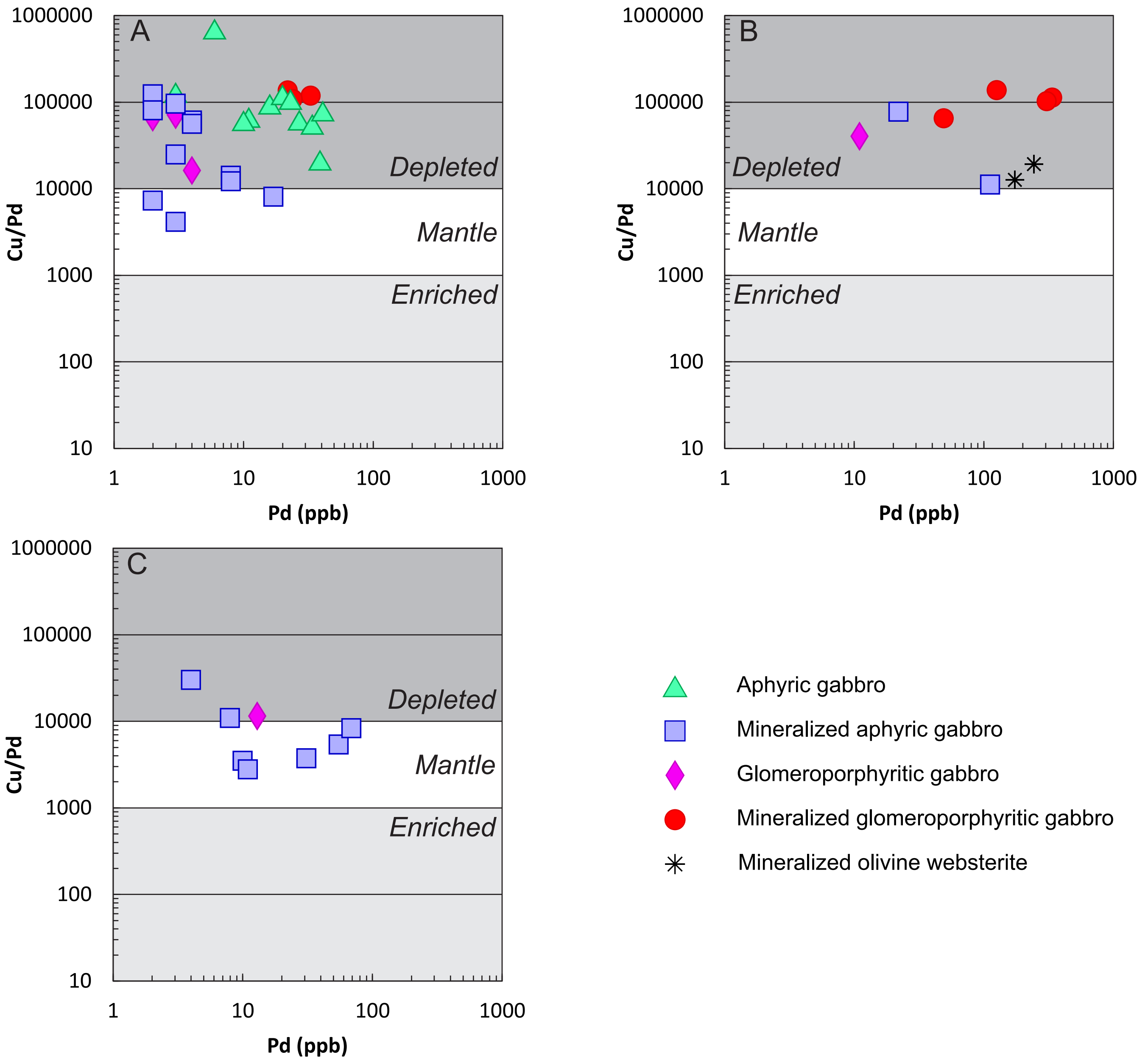

Figure 6. *Plot of Cu/Pd* vs. *Pd for mineralized and non-mineralized samples from the Howse Lake (A), Moss Lake (B) and Huckleberry (C) areas (adapted from Barnes* et al.*, 1993).*

IMS 4f Secondary Ion Mass Spectrometer (*see* Bruekner *et al.*, 2015 for full analytical methods). Where possible, multiple grains of each phase were analyzed for $\delta^{34}S$ in each sample to define possible variations in the isotope composition. Overall reproducibility, based on replicate standard analyses, is typically better than ± 0.4‰ (1σ). Results for the in-house sulphide standards, measured $^{34}S/^{32}S$ ratios and the calculated instrument mass fractionation (IMF) factors are summarized in Smith (2018). All values are reported in ‰ VCDT (Vienna Canyon Diablo Troilite).

Sulphur Isotope Data

The $\delta^{34}S$ ratios for chalcopyrite and pyrrhotite from gabbro samples in the Howse Lake area define a bimodal distribution, with populations between 3.6 to 4.2‰ and 8 to 12.7‰, respectively. The $\delta^{34}S$ ratios of chalcopyrite and pyrrhotite in sulphide-rich shales from Howse Lake range from 2.6 to 5.5‰. The sulphur isotope data in gabbro samples from the Moss Lake area range from 1 to 3.6‰, with a value of 1‰ from a single spot analysis of chalcopyrite in a

Table 2. The δ^{34}S ratios measured *in-situ* from chalcopyrite and pyrrhotite from mineralized gabbro samples and from sulphide-bearing sedimentary host rocks (Menihek and Thomson Lake formations) in the Howse Lake, Moss Lake and Huckleberry areas. Also included are the average δ^{34}S ratios measured from various rock types in the Frederickson Lake area (data from Gerbert, 1988) and the average δ^{34}S ratio from the Menihek Formation shale (from Cameron, 1983)

Location	Unit	Sample No.	Mineral	δ^{34}S	1σ
Howse Lake	Gabbro	17JC 025 A01	Chalcopyrite	10.8	0.5
				9.7	0.2
			Pyrrhotite	4	0.8
		17JC 037 A01	Chalcopyrite	9.4	0.5
				8	0.6
			Pyrrhotite	11.1	0.2
				10.7	0.4
		17JC 055 A01	Chalcopyrite	3.6	0.5
		17JC 100 A02	Chalcopyrite	4.2	0.4
			Pyrrhotite	8.4	0.3
		17JC 102 A01	Chalcopyrite	10.2	0.3
				12.7	0.5
	Sediment	17JC 054 B02	Pyrrhotite	3.7	0.6
				5.5	0.4
				3.9	0.5
			Chalcopyrite	2.6	0.7
Moss Lake	Gabbro	17JC 080 A02	Chalcopyrite	3.6	0.3
			Pyrrhotite	2.8	0.4
		17JC 088 A02	Chalcopyrite	2.6	0.3
			Pyrrhotite	1	1
	Sediment	17JC 083 A01	Chalcopyrite	1	0.6
Huckleberry	Gabbro	17JC 091 A02	Chalcopyrite	-1.1	1.1
				0.4	0.5
				-3.9	0.4
				0.2	0.2
				1.5	0.2
				1.4	0.2
			Pyrrhotite	-1.3	0.4
				-0.5	0.6
				-0.4	0.5
		17JC 095 A01	Chalcopyrite	-1.2	0.7
				0.5	0.3
				1.5	0.8
			Pyrrhotite	-0.8	0.4
				1.4	1
	Sediment	17JC C213	Chalcopyrite	1.8	0.6
				-0.3	0.7
			Pyrrhotite	4.4	0.4
				3.1	0.5

Location	Host rock	Reference	δ^{34}S	StDev
Frederickson Lake North	Gabbro	Gerbert (1988)	3.7	0.2
Frederickson Lake North	Sediment-hosted massive sulpide	Gerbert (1988)	9.2	0.1
Frederickson Lake	Sediment	Gerbert (1988)	3.5	0.9
Average Menihek	Sediment	Cameron (1983)	3.7	0.9

shale sample. Chalcopyrite and pyrrhotite from gabbros in the Huckleberry area have δ^{34}S ratios of -3.9 to 1.5‰, and chalcopyrite and pyrrhotite from a single shale sample have δ^{34}S ratios of -0.3 to 4.4‰.

Sulphur isotope data from magmatic sulphide deposits can be used to evaluate whether the sulphur source was magmatic vs. externally derived (crustal) sulphur, providing the isotopic composition of external-derived sulphur source is distinct from mantle-derived sulphur (Ripley and Li, 2003). In Figure 7, sulphur isotope data from the three study areas are plotted along with data from the Fredrickson Lake prospect (data from Gelbert, 1988). With the exception of δ^{34}S ratios for sediment-hosted massive sulphide mineralization at Frederickson Lake, all δ^{34}S ratios from sediment-hosted sulphides range between -0.3 and 5.5‰, which is similar to values for average Menihek Formation sulphides reported by Cameron (1983). These values are slightly higher than isotopic values for mantle-derived sulphur (0 ± 2‰; Ripley and Li, 2003), and therefore the data from sulphides in mineralized gabbro samples might allow determination as to whether there was significant assimilation of sulphur from the host sedimentary rocks or other sources.

The δ^{34}S ratios of chalcopyrite and pyrrhotite from mineralized gabbro samples from the Huckleberry area are within the range typical of mantle-derived sulphur (Figure 7; Ridley and Li, 2003). This is consistent with a magmatic sulphur source, with little or no externally derived sulphur. The δ^{34}S isotopic compositions of chalcopyrite and pyrrhotite from samples in the Howse Lake, Moss Lake and Frederickson Lake areas are higher than the range of uncontaminated mantle-derived magmas (−2 to +2‰; Ripley and Li, 2003), suggesting an external sulphur source. The similarities between δ^{34}S values from sulphides in gabbros in the Moss Lake and Frederickson Lake areas and the associated host sedimentary rocks (Figure 7) pro-

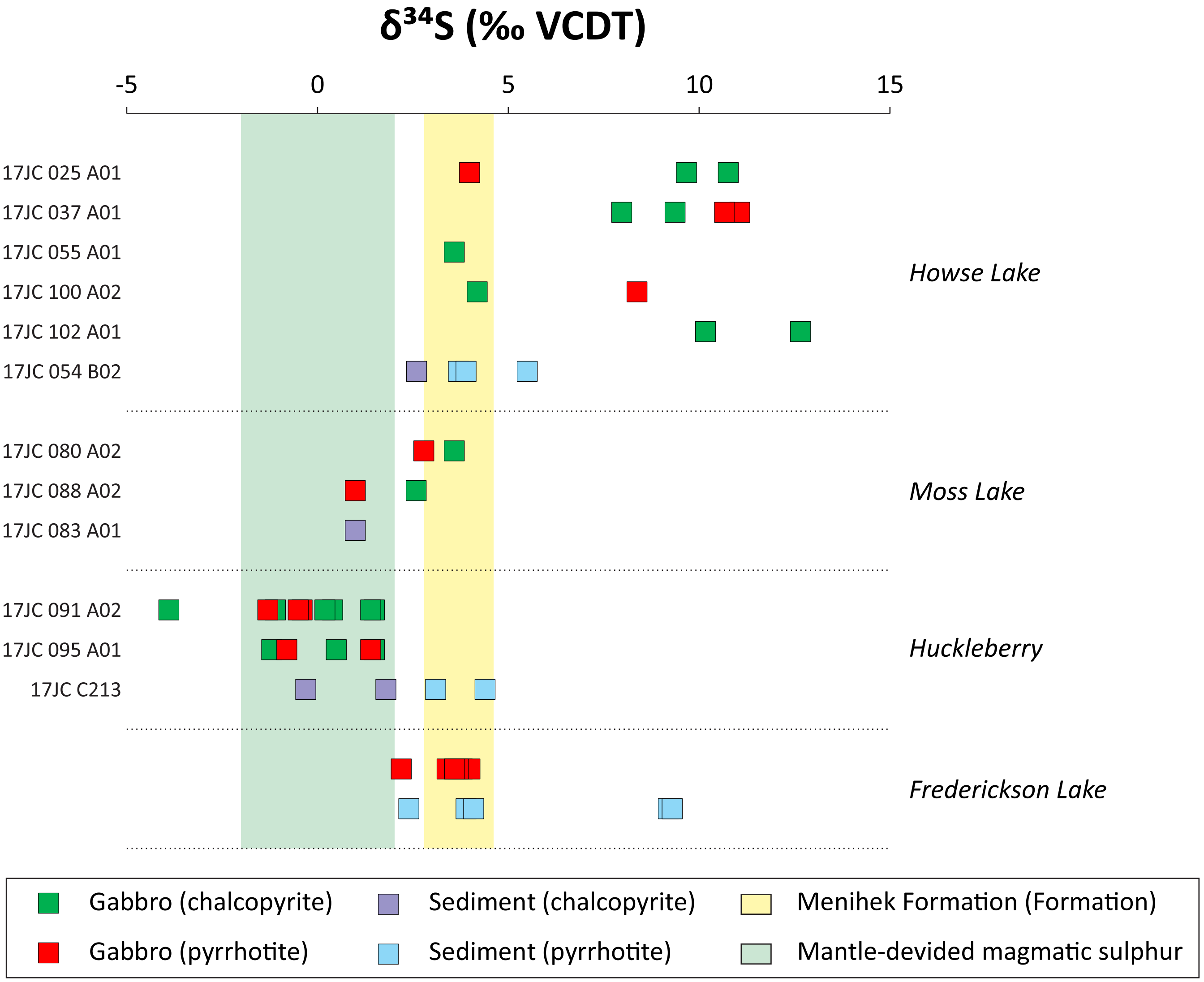

Figure 7. *The* $\delta^{34}S$ *ratios measured* in-situ *from chalcopyrite and pyrrhotite from mineralized gabbro samples and from sulphide-bearing sedimentary host rocks (Menihek and Thomson Lake formations). Data from the Frederickson Lake area from Gerbert (1988). Sulphur isotope ratio for average Menihek Formation from Cameron (1983), isotopic values for mantle-derived sulphur from Ripley and Li (2003).*

vide strong evidence for assimilation of sulphur from the county rocks.

A wide range of $\delta^{34}S$ ratios were obtained from sulphides in mineralized gabbros from the Howse Lake area (Figure 7). Three analyses returned sulphur isotope ratios similar to those from sulphides in the country rocks, with other analyses yielding isotopically heavier ^{34}S values (up to 12.7‰). This suggests some source of externally derived sulphur into the magma other than the surrounding country rocks. Gerbert (1988) showed that the sediment-hosted massive sulphides at Frederickson Lake have isotopically heavy $\delta^{34}S$ values (up to 9.3‰), and thus assimilation of similar material may be a potential source of the externally derived sulphur. It is also noted that in-situ analysis of chalcopyrite and pyrrhotite in the same thin section yielded variations in $\delta^{34}S$ of up to 6.8‰ (sample 17 JC 025 A01). This disequilibrium is not typical of high-temperature magmatic systems, where fractionation between sulphide minerals is generally low (Seal II, 2006).

DISCUSSION AND CONCLUSIONS

Mafic and ultramafic sills of the Gerido Intrusive Suite crop out extensively in the Hurst and Retty zones of the Labrador Trough in western Labrador and adjacent Québec. These sills are mostly aphyric gabbros, lesser glomeroporphyritic gabbros (containing >20% plagioclase glomerocrysts) and ultramafic units (peridotite and olivine websterite). Lithogeochemical data indicate little geochemical variation between mafic rocks in the three study areas (Howse Lake, Moss Lake, and Huckleberry). Immobile elements suggest that all the units are basaltic and have tholeiitic affinities. The The Th–Nb crustal input plots indicate that most samples plot within the MORB-OIB array (transitional between N-MORB and E-MORB) and suggest minimal contamination by crustal assimilation. This is consistent with previous geochemical interpretations of the Gerido Intrusive Suite, which suggest a lithotectonic model of rift-related magmatism in an extensional environment associated with the formation pull-apart basins, along the continental margin prior to the deformation that formed the New Québec Orogen (Skulski *et al.*, 1993).

Sulphide mineralization is common in the Gerido Intrusive Suite, and some samples of mineralized gabbro contain up to 20% sulphides (pyrrhotite, chalcopyrite and pentlandite ± pyrite). The SEM-MLA analysis also identified a number of discrete PGE minerals in gabbro and olivine websterite samples, and most PGE minerals having a chemical composition of Pd–Bi–Te. Other PGE mineral compositions identified include Pd–Hg–Te (Howse Lake), Pd–Ag–Pb–Te and Pd–Te–Se (Moss Lake) and Pt–Pd–Bi–Te (Huckleberry).

Mineralized aphyric and glomeroporphyritic gabbro from the Howse Lake area contains up to 0.41% Cu and 621 ppm Ni, with low PGE contents (Pt + Pd <100 ppb). Samples from the Moss Lake area are essentially non-mineralized, with <0.06% Cu, <178 ppm Ni and <91 ppb Pt + Pd. Aphyric and glomeroporphyritic gabbro from the Huckleberry area in Québec is the most strongly mineralized, with samples yielding up to 1.22% Cu and 0.20% Ni, and up to 436 ppb Pt + Pd. Mineralized olivine websterite from the Huckleberry area has Cu contents up to 0.47% with up to 0.17% Ni and 317 ppb Pt + Pd. Mineralized samples have Cu/Ni ratios >2, similar to other Cu-rich magmatic sulphide deposits, *e.g.*, Duluth Complex, Minnesota (Theriault *et al.*, 2000).

The Cu/Pd ratios and sulphur isotope analysis were used to assess the origin of the sulphide mineralization in each of the three study areas. In the Howse Lake area, mineralized and non-mineralized samples typically have Cu/Pd ratios above normal mantle values, which may be related to derivation under sulphur-saturated melting conditions or the depletion of Pd *via* early sulphide segregation during the ascent of magmas. The latter option implies PGE-rich sulphide deposits may occur elsewhere in the mineralizing system (Barnes *et al.*, 1993), but does not provide any clues as to its location(s). Nevertheless, the presence of PGE-rich mineralization at nearby Frederickson Lake supports the idea that similar PGE-rich zones could occur at Howse Lake.

Sulphur isotope data show that pyrrhotite and chalcopyrite have markedly positive sulphur isotope ratios ($\delta^{34}S$ = +3.6 to 12.7‰), consistent with a crustal sulphur source. This raises another possibility for the high Cu/Pd ratios, *i.e.*, elevated Cu contents due to the assimilation of Cu-rich sedimentary rocks that would have increased Cu contents without affecting the PGE contents. The Menihek Formation contains sources for Cu contamination, including massive to heavily disseminated pyrrhotite, pyrite and chalcopyrite in argillites at Howse Lake (up to 4500 ppm Cu; Swinden and Santaguida, 1994), and base-metal-rich semi-massive sulphides in chert argillites at Frederickson Lake, east of Howse Lake (best drillhole interception of 14.07% Zn, 2.25% Cu, 1.76% Pb over 1.2 m; Clark and Wares, 2005). The presence of Hg-bearing PGE minerals and identification of sulphide droplets close to the margins of the gabbro sills also support the assimilation of metals and sulphides from the country rock. This type of contamination has been used to explain high Cu/Pd ratios in other Cu-rich magmatic sulphide occurrences, *e.g.*, in the Duluth Complex, Minnesota (Theriault *et al.*, 2000).

At Moss Lake, gabbro samples have Cu/Pd ratios close to mantle values and sulphur isotope data, suggesting that sulphur was derived from the sedimentary host rocks. The low base-metal contents of these gabbros, and the lack of evidence for significant PGE-enrichment, suggest that these gabbros have a lower exploration potential.

Highly mineralized gabbro and ultramafic samples from the Huckleberry area in Québec have similar Cu/Pd ratios to samples from the Howse Lake area (*i.e.*, they are depleted in Pd relative to mantle values). However, the sulphur isotope data are consistent with a magmatic sulphur source, with little or no assimilation of crustal sulphur. In this case, higher Cu/Pd ratios are not likely due to the assimilation of Cu-rich sedimentary rocks, and must instead be a feature of the magmas, inherited from source melting or earlier sulphide segregation. The information from the Huckleberry area imply that the Gerido Intrusive Suite remains prospective for Ni, Cu and PGE mineralization throughout the Hurst and Retty zones of the Labrador Trough.

ACKNOWLEDGMENTS

Thanks go to Wayne Tuttle, who provided vital assistance and logistical support without which this project would be impossible. Oksana Choulik and the staff at the McGill Subarctic Research Station are thanked for their hospitality during our stay in Schefferville. Fieldwork in Schefferville was greatly aided by the support of Jared Butler and his bedrock-mapping team, and Northern Shield Resources are thanked for providing a tour of their Huckleberry property. Andrew Kerr and John Hinchey provided helpful reviews of earlier drafts of this contribution. Glen Piercey of the CREAIT SIMS lab assisted in the δ^{34}S. The MLA-SEM analyses were performed under the supervision of David Grant and Dylan Goudie.

REFERENCES

Baragar W.R.A.
1967: Wakuach Lake, Québec–Labrador. Geological Survey of Canada, Memoir 344, 174 pages.

Barnes, S.-J. and Lightfoot, P.C.
2005: Formation of magmatic nickel sulfide deposits and processes affecting their copper and platinum group element contents. Economic Geology 100th Anniversary Volume, pages 179-214.

Barnes, S.-J., Couture, J.F., Sawyer, E.W. and Bouchaib, C.
1993: Nickel–copper occurrences in the Belleterre-Angliers Belt of the Pontiac Subprovince and the use of Cu–Pd ratios in interpreting platinum-group elements distributions. Economic Geology, Volume 88, pages 1402-1418.

Barnes, S.J., Cruden, A.R., Arndt, N. and Saumur, B.M.
2016: The mineral system approach applied to magmatic Ni–Cu–PGE sulphide deposits. Ore Geology Reviews, Volume 76, pages 396-316.

Barnes, S.J., Mungall, J.E., Le Vaillant, M., Godel, B., Lesher, C.M., Holwell, D., Lightfoot, P.C., Krivolutskaya, N. and Wei, B.
2017: Sulfide–silicate textures in magmatic Ni–Cu–PGE sulfide ore deposits: Disseminated and net-textured ores. The American Mineralogist, Volume 102(3), pages 473-506.

Bilodeau, C. and Caron-Côté, E.
2018: Géologie de la région de la rivière Arnaud, provinces du Supérieur (Minto) et de Churchill (Fosse du Labrador), secteur de Kangirsuk, Nunavik, Québec, Canada. Ministère de l'Énergie et des Ressources naturelles, Québec, Bulletin Géologique.

Bleeker, W. and Kamo, S.L.
2018: Extent, origin, and deposit-scale controls of the 1883 Ma Circum-Superior large igneous province, northern Manitoba, Ontario, Québec, Nunavut and Labrador. Targeted Geoscience Initiative: 2017 Report of Activities, Volume 2. *Edited by* N. Rogers. Geological Survey of Canada, Open File 8373, pages 5-14.

Bloomer, R.O.
1955: Geology of the Howse Lake area, Labrador. Labrador Mining and Exploration Company Limited and Hollinger North Shore Exploration Company Limited. Newfoundland and Labrador Geological Survey, Assessment File 23O/0005, 70 pages.

Brueckner, S.B., Piercey, S.J., Layne, G.D., Piercey, G. and Sylvester, P.J.
2015: Variations of sulphur isotope signatures in sulphides from the metamorphosed Ming Cu (–Au) volcanogenic massive sulphide deposit, Newfoundland Appalachians, Canada. Mineralium Deposita, Volume 50, pages 619-640.

Butler, D. and McLean, S.
1992: First year assessment report on geological and geochemical exploration for licenses 440m-441m and 453m on claims in the Moss Lake and Marion Lake areas, western Labrador. Falconbridge Limited. Newfoundland and Labrador Geological Survey, Assessment File 23I/13/0075, 37 pages.

Cameron, E.M.
1983: Genesis of Proterozoic iron-formation: Sulphur isotope evidence. Geochimica Cosmochirnica Acta, Volume 47, pages 1069-1074.

Clark, T. and Wares, M.
2005: Lithotectonic and metallogenic synthesis of the New Québec Orogen (Labrador Trough). Ministère des Ressources Naturelles, Québec, MM 2005-01, 175 pages.

Conliffe, J. and Smith, A.
2018: Geochemical data from Montagnais Gabbro sills and associated rocks in the Labrador Trough (NTS map areas 23I/12, 13, 23J/16, 23O/01 and 02). Government of Newfoundland and Labrador, Department of Natural Resources, Geological Survey, Open File LAB/1723, 8 pages.

Evans, J.L.
1978: The geology and geochemistry of the Dyke Lake area (parts of 23J/8, 9), Labrador. Government of Newfoundland and Labrador, Department of Mines and Energy, Mineral Development Division, Report 78-04, 43 pages.

Findlay, J.M.
1996: Petrology, geochemistry and evolution of the Labrador Trough Basaltic Suite, Labrador and New Québec. Unpublished Ph.D. thesis, University of Ottawa, 612 pages.

Findlay, J.M. and Fowler, A.D.
1989: First year assessment report on geological and geochemical exploration for license 242m on claims in the Howse Lake area, Labrador. Cliff Resources Corporation and Canaustra Gold Exploration Limited. Newfoundland and Labrador Geological Survey, Assessment File 23O/0035, 28 pages.

Findlay, J.M., Fowler, T.D. and Birkett, T.C.
1990: Geology of the Howse Lake area, western Labrador. Geological Survey of Canada, Open File 2204, 70 pages.

Findlay, J.M., Parrish, R.R., Birkett, T.C. and Watanabe, D.H.
1995: U–Pb ages from the Nimish Formation and Montagnais glomeroporphyritic gabbro of the central New Québec Orogen, Canada. Canadian Journal of Earth Sciences, Volume 32, pages 1208-1220.

Frarey, M.J. and Duffell, S.
1964: Revised stratigraphic nomenclature for the central part of the Labrador Trough. Geological Survey of Canada, Paper 64-25, 13 pages.

Gerbert, J.
1988: The metallogeny of Cu–Ni and Zn–Cu–Pb deposits of the Frederickson Lake area, central Labrador Trough. Unpublished M.Sc. thesis, McGill University, 166 pages.

Le Gallais, C.J. and Lavoie, S.
1982: Basin evolution of the Lower Proterozoic Kaniapiskau Supergroup, central Labrador Miogeocline (Trough), Québec. Bulletin of Canadian Petroleum Geology, Volume 30, pages 150-160.

Machado, N., Clark, T., David, J. and Goulet, N.
1997: U–Pb ages for magmatism and deformation in the New Québec Orogen. Canadian Journal of Earth Sciences, Volume 34, pages 716-723.

Naldrett, A.J.
2010: From the mantle to the bank: The life of a Ni–Cu–(PGE) sulfide deposit. South African Journal of Geology, Volume 113.1, pages 1-32.

Pearce, J.A.
1996: A user's guide to basalt discrimination diagrams. *In* Trace Element Geochemistry of Volcanic Rocks; Applications for Massive Sulphide Exploration. Short Course Notes, Geological Association of Canada, Volume 12, pages 79-113.

2008: Geochemical fingerprinting of oceanic basalts with applications to ophiolite classification and the search for Archean oceanic crust. Lithos, Volume 100, pages 14-48.

Ripley, E.M. and Li, C.S.
2003: Sulfur isotope exchange and metal enrichment in the formation of magmatic Ni–Cu–(PGE) deposits. Economic Geology, Volume 98, pages 635-641.

Rohon, M.-L., Vialette, Y., Clark, T., Roger, G., Ohnenstetter, D. and Vidal, P.
1993: Aphebian mafic–ultramafic magmatism in the Labrador Trough (New Québec): its age and the nature of its mantle source. Canadian Journal of Earth Sciences, Volume 30, pages 1582-1593.

Ross, P.S. and Bedard, J.H.
2009: Magmatic affinity of modern and ancient subalkaline volcanic rocks determined from trace-element discriminant diagrams. Canadian Journal of Earth Sciences, Volume 46, pages 823-839.

Scott, F., Bowie, G. and Tang, K.K.
1988: Report on the 1987 exploration results, permit 774, Blue Lake district. Fonteneau Resources Ltd., Énergie et Ressources naturelles, Québec, Assessment Report GM 47075, 14 pages.

Seal II, R.R.
2006: Sulfur isotope geochemistry of sulfide minerals. Reviews in Mineralogy and Geochemistry, Volume 61, pages 633-677.

Skulski, T., Wares, R.P. and Smith, A.D.
1993: Early Proterozoic (1.88–1.87 Ga) tholeiitic magmatism in the New Québec orogen. Canadian Journal of Earth Sciences, Volume 30, pages 1505-1520.

Smith, A.
2018: Petrographic, geochemical and sulphur isotope studies of the Montagnais Gabbro, Labrador Trough, Canada – Implications for Ni-Cu-PGE exploration potential. Unpublished B.Sc. thesis, Memorial University of Newfoundland, 107 pages.

Smith, A., Conliffe, J. and Wilton, D.
2018: Montagnais Gabbro of western Labrador: Preliminary geological and petrographic data and implications for Ni–Cu–PGE mineralization. *In* Current Research. Government of Newfoundland and Labrador,

Department of Natural Resources, Geological Survey, Report 18-1, pages 153-166.

Sun, S.S. and McDonough, W.F.
1989: Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. *In* Magmatism in the Ocean Basins. *Edited by* A.D. Saunders and M.J. Norry. Geological Society of London Special Publications, Volume 42, pages 313-345.

Swinden, H.S. and Santaguida, F.
1993: Argillite-hosted sulphide occurrences in the eastern part of the Labrador Trough. *In* Current Research. Government of Newfoundland and Labrador, Department of Mines and Energy, Geological Survey Branch, Report 93-1, pages 401-418.

1994: Sulphide occurrences in clastic sedimentary rocks in the Howse Zone, western Labrador. *In* Current Research. Government of Newfoundland and Labrador, Department of Mines and Energy, Geological Survey Branch, Report 94-1, pages 253-261.

Thériault, R.D., Barnes, S.-J. and Severson, M.J.
2000: Origin of Cu–Ni–PGE sulfide mineralization in the Partridge River Intrusion, Duluth Complex, Minnesota. Economic Geology, Volume 95, No. 5, pages 929-943.

Thériault, R. and Beauséjour, S.
2012: Carte géologique du Québec. Ministère des Richesses naturelles, Québec.

Vaillancourt, C., Bliss, L. and Murray, G.
2016: Report on the Huckleberry Property, reconnaissance programs 2014-2015. Northern Shield Resources Inc., Énergie et Ressources naturelles, Québec, Assessment Report GM 69550, 109 pages.

Wardle, R.J.
1982: Geology of the south-central Labrador Trough – Map 1. Government of Newfoundland and Labrador, Department of Mines and Energy, Mineral Development Division, Map 82-005.

Wardle, R.J. and Bailey, D.G.
1981: Early Proterozoic sequences in Labrador. *In* Proterozoic Basins of Canada. *Edited by* F.H.A. Campbell. Geological Survey of Canada, Paper 81-10, pages 331-359.

Wardle, R.J., Ryan, B., Nunn, G.A.G. and Mengel, F.C.
1990: Labrador segment of the Trans-Hudson Orogen: crustal development through oblique convergence and collision. *In* The Early Proterozoic Trans-Hudson Orogen of North America. *Edited by* J.F. Lewry and M.R. Stauffer. Geological Association of Canada, Special Paper 37, pages 353-369.

Winchester, J.A. and Floyd, P.A.
1977: Geochemical discrimination of different magma series and their differentiation products using immobile elements. Chemical Geology, Volume 20, pages 325-343.

Zajac, I.S.
1974: The stratigraphy and mineralogy of the Sokoman Iron Formation in the Knob Lake area, Québec and Newfoundland. Geological Survey of Canada, Bulletin 220, 159 pages.