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Targeted Geoscience Initiative 4: Canadian Nickel-Copper-Platinum Group Elements-Chromium Ore Systems — Fertility, Pathfinders, New and Revised Models

Mafic intrusive rocks from the Bird River intrusive suite, Bird River greenstone belt, southeast Manitoba

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ABSTRACT

This study presents new field, petrographic, and geochemical observations for the Coppermine Bay and Euclid Lake intrusions of the Bird River greenstone belt, allowing for comparison with the Mayville and other Bird River sill intrusions in southeast Manitoba. The mafic-dominated Coppermine Bay intrusion, located in the westernmost part of the southern arm of the Bird River greenstone belt, is texturally and petrographically similar to the mafic part of the mafic-ultramafic Euclid Lake intrusion, located 34 km to the northeast, at the northeast margin of the belt's northern arm. The mafic components of the Coppermine Bay and Euclid Lake intrusions possess textural, compositional, and geochemical similarities with the Mayville and with mafic parts of other Bird River sill intrusions. Combined with geochemical and geochronological investigations, a petrogenetic linkage of these mafic-ultramafic intrusions is proposed through a widespread Neoarchean Bird River magmatic event at ca. 2743 Ma, referred to as the Bird River intrusive suite. TiO_2 and Zr contents, as well as rare earth elements profiles and plagioclase chemistry, may be useful geochemical tools to successfully discriminate and identify potentially fertile intrusions beyond traditionally explored sectors in the Bird River greenstone belt.

INTRODUCTION

In 2011, the Geological Survey of Canada (GSC), through the Targeted Geoscience Initiative 4 (TGI-4) program, in collaboration with the Manitoba Geological Survey (MGS), initiated a multi-year project to characterize mafic and ultramafic intrusions and associated Ni-Cu-(PGE) and Cr-(PGE) orthomagmatic mineralization within the Neoarchean Bird River greenstone belt (BRGB) of southeast Manitoba.

Building on detailed work done in the mid- to late 1980s on the well exposed Chrome property located within the central part of the southern arm of the BRGB (e.g. Scoates, 1983; Scoates et al., 1986, 1989; Williamson, 1990), the current investigation focuses on mafic-ultramafic intrusions located in both the northern and southern arms of the BRGB (Fig. 1) with special emphasis on characterizing the mafic component of intrusive bodies and providing a geological framework for ongoing geochronological work carried out across the belt. More specifically, textural, petrographic, and geochemical results from the less studied Coppermine Bay and the Euclid Lake intrusions, within the southern and northern arms of the BRGB, respectively, are presented and compared with the Mayville intrusion, which is economically the most significant intrusion of the belt's northern arm.

PREVIOUS AND CURRENT WORK

For more than a century the BRGB has been the subject of extensive geological investigations, including regional mapping initiatives and targeted economic mineral studies. Most recently, the MGS carried out regional bedrock mapping initiatives that mainly focussed on the southern (Gilbert et al., 2008) and northern portions (Yang et al., 2012, 2013) of the belt. Readers are referred to Gilbert et al. (2013) for an introduction to the geology and an overview of previous and current work carried out in the belt.

Numerous mafic to ultramafic intrusions containing significant Cr-(PGE) and Ni-Cu-(PGE) mineralization in both arms of the BRGB were recognized early. However, it was not until the discovery of Ni-Cu occurrences east of the Maskwa River in 1917 (Bateman, 1943) that more sustained mineral exploration led to significant discoveries of Ni-Cu and chromite deposits and occurrences hosted in mafic-ultramafic intrusive rocks of the Bird River area (Bird River Sill-BRS), in the southern arm of the BRGB.

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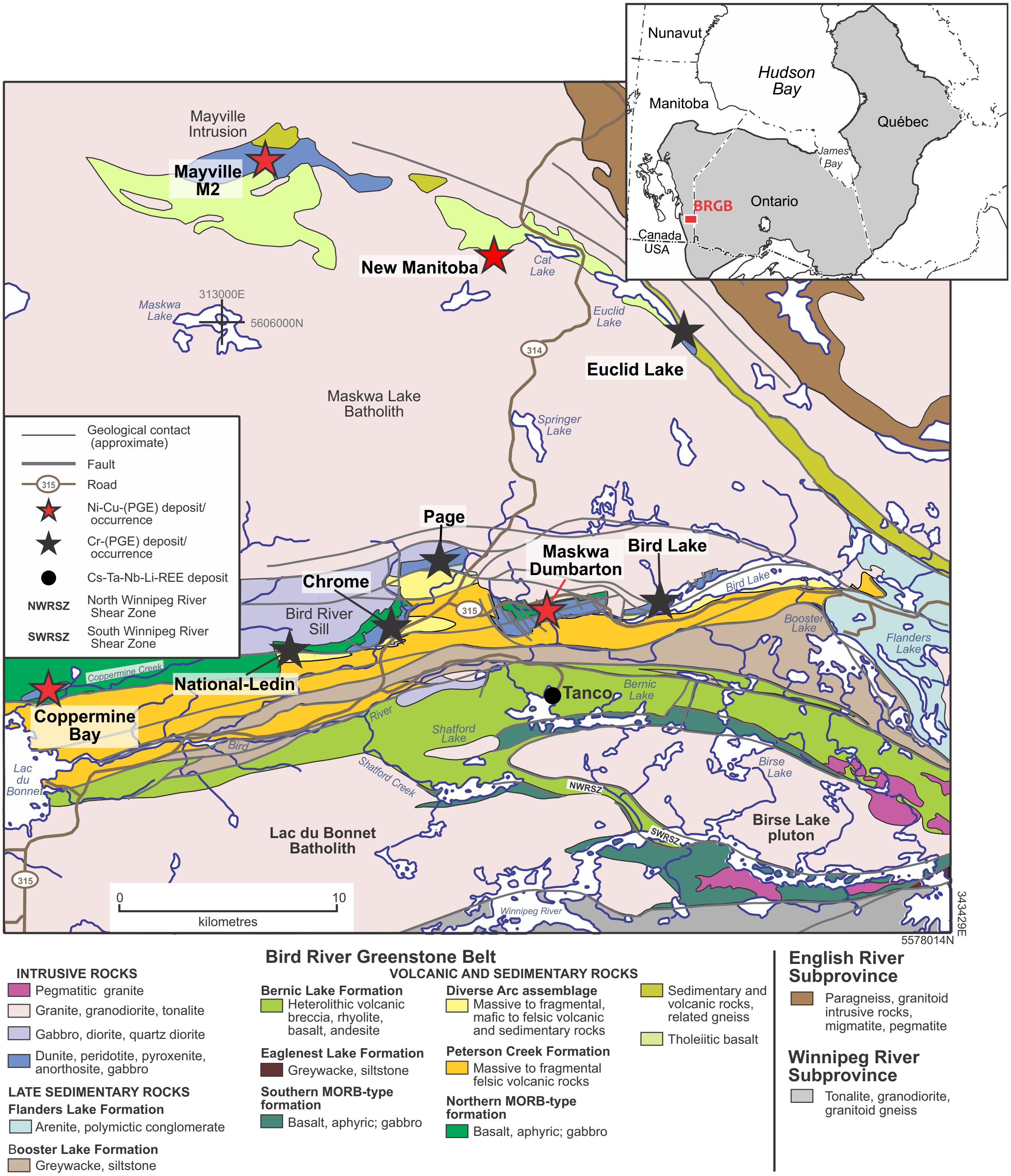


Figure 1. Simplified geology of the northern and southern arms of the Bird River greenstone belt (BRGB) showing the main mafic and ultramafic igneous bodies and associated Ni-Cu-(PGE) and Cr-(PGE) deposits/occurrences, as well as the TANCO Cs-Ta-Nb-Li-REE deposit (modified from Gilbert et al., 2013).

Table 1. Compilation of historical production and resource calculations for nine Ni-Cu-(PGE) and Cr-PGE) deposits/occurrences of the Bird River greenstone belt, southeast Manitoba.

Deposit / Intrusion	District	Ore (Mt)	Ni (%)	Cu (%)	Pt+Pd (g/t)	Cr_2O_3 (%)	Data Source
M2 - Mayville	Northern arm	31.80	0.18	0.45	0.19		Mustang Minerals Corp., 2013
New Manitoba*	Northern arm	0.60	0.24	0.58			Manitoba Inventory File No. 217
Maskwa	Southern arm – BRS	8.27	0.61	0.13	0.42		Coats et al., 1979; Mustang Minerals Corp., 2013
Dumbarton*	Southern arm – BRS	1.54	0.81	0.30			Coats et al., 1979
Page & Ore Fault	Southern arm – BRS	0.55	0.94	0.56	0.35		Marathon PGM Corp., 2008
Euclid Lake*	Northern arm	4.69				6.44	ILAM Associates, 1988
Bird Lake*	Southern arm – BRS	1.12				7.53	ILAM Associates, 1988
Chrome*	Southern arm – BRS	1.34				9.65	ILAM Associates, 1988
Page*	Southern arm – BRS	1.71				7.40	ILAM Associates, 1988

*Not NI 43-101 compliant

Since the initial discoveries, sporadic exploration over the years has led to Ni-Cu and Cr mineral resource estimates (Table 1). Of specific relevance to this contribution, brief overviews of exploration work carried out on the Coppermine Bay, Euclid Lake, and Mayville intrusions are presented herein.

Coppermine Bay Intrusion

Gabbroic rocks of the Coppermine Bay intrusion (Wards claim), in the western extremity of the BRGB's southern arm, were interpreted by Bannatyne and Trueman (1982) and more recently by Gilbert et al. (2008) as a distinct intrusive unit that does not correlate with other BRS intrusions, despite the presence of Cu-Ni-(PGE) and Cr mineralization. The first report of chromite within the Coppermine Bay gabbro dates back to 1929 (Watson, 1982); however, the chromite lenses were interpreted as too small and scattered to be of economic interest (e.g. Bateman, 1943). Since then, Cu-Ni and PGE intersections reported from a single drillhole in 1973 (0.42% Cu, 0.24% Ni, and 2.2 g/t Pt+Pd over 12.2 m; Canex Placer Ltd., 1973) revitalized interest in the economic potential of the intrusion and led Marathon PGM Corporation and Gossan Resources Limited to pursue sporadic exploration in the area between 2004 and 2010. The best results were obtained from a grab sample that graded up to 0.44% Cu%, 0.21% Ni, and 2.6 g/t Pt+Pd (Gossan Resources Ltd., 2007 – reporting Marathon PGM Corporation's initial results).

Euclid Lake Intrusion

The Euclid Lake intrusion, located in the eastern extremity of the BRGB's northern arm, has been interpreted to be an extension of the BRS (e.g. Bateman, 1942; Trueman, 1980). Chromite mineralization was first discovered on the property in 1942 and several chromite resource estimates were subsequently made in the 1980s, mainly based on compilation of historical diamond-drill records (Table 1). Since then, some prospecting activities were carried by Exploratus Elementis Diversis Ltd. in the 1990s and more recently, Mustang Minerals Corporation ("Mustang") carried out geophysical and geological surveys in 2005 and drilled three diamond drillholes in 2011.

Mayville Intrusion

The Mayville intrusion was initially delineated during regional bedrock mapping carried out in the northern arm of the BRGB by the MGS in the late 1940s (Springer 1949, 1950), but it was not until the mid-1980s that the first geological map was published for the western part of the intrusion (Macek, 1985). Ni-Cu sulphide mineralization and chromite occurrences (e.g. Theyer, 1985) led several exploration companies (Exploratus Ltd., Falconbridge Ltd., and TANCO) to conduct detailed geological mapping; other thematic studies were subsequently carried out by the MGS (Peck and Theyer, 1998; Peck et al., 1999, 2002). More recently, Mustang completed detailed geological mapping of the intrusion and updated mineral resource estimates for the M2 Ni-Cu-(PGE) deposit (Table 1). In 2012, the MGS remapped the Mayville intrusion and surrounding area at 1: 12 500 scale, which was updated to 1:10 000 scale in 2014 (Yang, 2014).

PETROGRAPHY AND GEOCHEMISTRY

For simplicity, the prefix "meta" is not used in the following section with the understanding that all rocks have undergone greenschist- to amphibolite-facies metamorphism. Primary minerals have been mostly replaced, but original textures and crystal forms are usually preserved, thus pseudomorphs (e.g. pyroxene) were often used to determine the primary mineralogy.

Coppermine Bay Intrusion

The Coppermine Bay intrusion consists of a series of relatively poorly exposed outcrops distributed along a 2 km long by 400 m wide, northeast-trending corridor in which a Cu-Ni-(PGE) mineralized zone with an 800

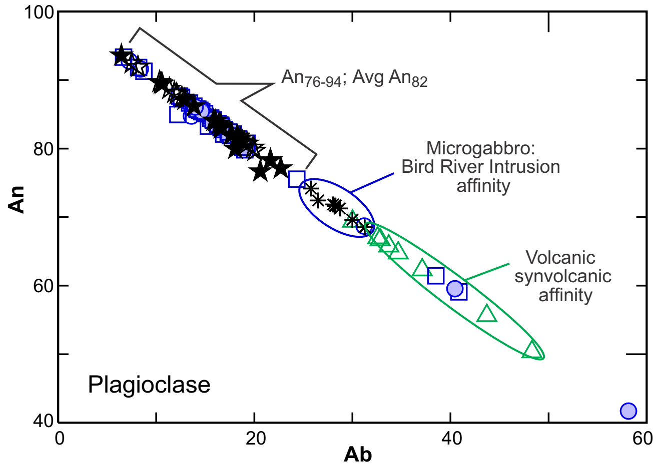


Figure 2. Anorthite (An) versus albite (Ab) components of plagioclase from leuco- to anorthositic gabbro, gabbro, melagabbro, microgabbro, and mafic volcanic units from the Coppermine Bay and Euclid Lake intrusions. Refer to the legend in Figure 4.

m strike length was delineated by Gossan Resources Ltd. (2007). Exposed lithologies include gabbro, leucogabbro, anorthositic gabbro, and rare pyroxenite intercalated with volcanic rocks from the Northern-MORB formation (Gilbert et al., 2008). The Coppermine Bay rocks are medium- to coarse-grained and are composed of calcic plagioclase (Fig. 2) and magnesiohornblende with minor biotite, chlorite, carbonate, and local skeletal ilmenite. Although volumetrically less significant than other lithologies, melagabbroic rocks, which were mainly intersected in drill core, consist of magnesiohornblende and calcic plagioclase (Fig. 2), with variable amounts of biotite, chlorite, and epidote. These units are usually fine- to medium-grained and grain size coarsens generally with increasing plagioclase abundance. The melagabbroic rocks are quite significant as they are the main host-lithology for the Cu-Ni-(PGE) disseminated sulphide mineralization and for the chromite mineralization that grades up to 10.7% Cr_2O_3 locally. Gabbroic, leucogabbroic, and anorthositic rocks of the Coppermine Bay intrusion (Fig. 3a) are texturally similar to other gabbroic rocks of the BRS (Fig. 3b,c,d).

The Coppermine Bay gabbroic rocks display similar contents of MgO, SiO_2, FeO_T, TiO_2, and Zr to those in gabbro and anorthositic gabbro samples obtained by Mealin (2008) from the Chrome property of the BRS (Fig. 4). Rare earth elements (REE) ratios are constant to slightly depleted from La to Nd and REE profiles are relatively flat or show slightly positive slope from Gd to Lu (Fig. 5a). Well defined Eu anomalies are noticeable for most samples and REE profiles exhibit some similarities with the ones obtained at the Chrome property (Fig. 5a).

Mafic volcanic rocks are characteristically dark grey, fine-grained and consist of an amphibole-plagioclase-chlorite assemblage with minor apatite. Altough the MgO and SiO_2 contents are comparable, the FeO_T, TiO_2, and Zr contents are slightly higher than those of the anorthositic to melagabbroic units of the Coppermine Bay intrusion.

Distinct REE profiles, with overall enrichment, positive slope from La to Nd, and minor negative Eu anomalies characterize the volcanic rocks from the intrusion-related gabbroic units (Fig. 5a).

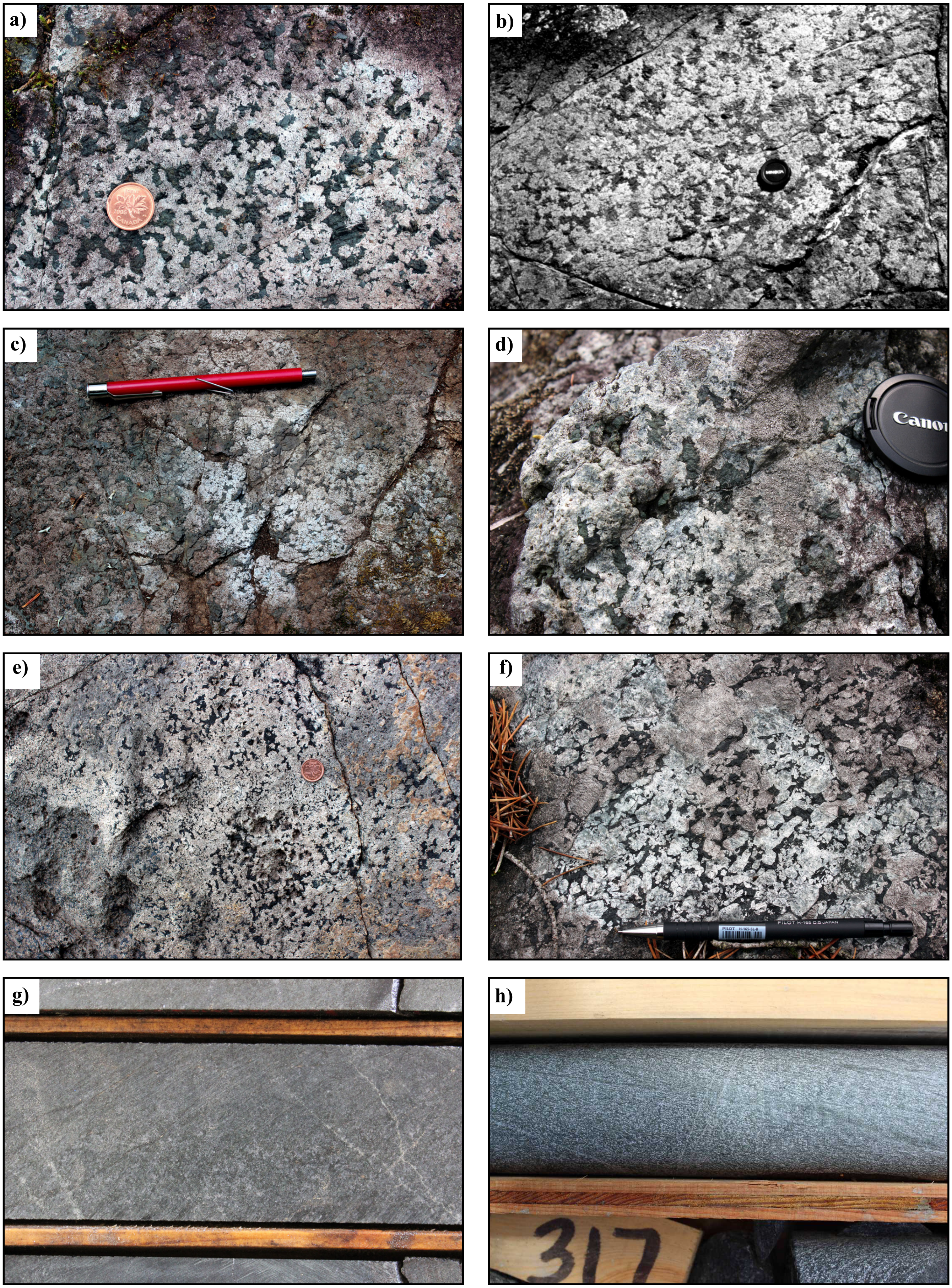
Microgabbro observed in drill core at Coppermine Bay, has sharp to diffuse contacts with bounding gabbroic to leucogabbroic and mafic volcanic units (Fig. 3g). They predominantly consist of fine-grained to aphanitic rocks composed mainly of calcic plagioclase (Fig. 2) and amphibole with minor chlorite. Whereas they possess comparable MgO, SiO_2, FeO_T concentrations to those from coarser gabbroic rock units, two samples exhibit distinctively higher TiO_2 and Zr contents. The higher TiO_2 and Zr contents are comparable to abundances encountered within mafic volcanic units as well as in Northern and Southern MORB-type formations of Gilbert et al. (2008) (Fig. 4). This suggests a volcanic affinity for these rocks, which is also reflected by their REE profiles (Fig. 5a).

Euclid Lake Intrusion

The Euclid Lake intrusion is a poorly exposed mafic to ultramafic intrusion in which Bateman (1943), Springer (1950), and Trueman (1997) reported a few surface exposures of peridotite that contained thin layers of disseminated and dense chromite over a distance of 15 m. Examination of the 2011 drillholes, led Bécu et al. (2013) to propose that the Euclid Lake intrusion consists of an ultramafic zone intercalated between two mafic zones. This differs from the ultramafic sequence overlain by a mafic sequence that is typically observed elsewhere in BRS intrusions.

Medium- to coarse-grained gabbro, leucogabbro, and anorthositic gabbro (Fig. 3e) are the main rock units encountered in a recent cross-section investigation (Bécu et al., 2013). These rocks are texturally sim-

Figure 3 (opposite page). Outcrop and drill-core photographs showing textural similarities between gabbroic units from mafic-ultramafic intrusions in the Bird River greenstone belt. **a)** Medium-grained leucogabbro of the Coppermine Bay intrusion. **b)** Medium-grained leucogabbro of the Chrome intrusion (from Williamson, 1990). **c)** Medium-grained leucogabbroic to anorthositic unit of the Maskwa-Dumbarton intrusion. **d)** Medium- to coarse-grained leucogabbro to anorthosite of the Bird Lake intrusion. **e)** Medium-grained anorthositic to leucogabroic unit of the Euclid Lake intrusion. **f)** Medium- to coarse-grained leucogabbro to anorthosite of the Mayville intrusion. **g)** Fine-grained microgabbro unit of the Coppermine Bay intrusion. **h)** Fine- to medium-grained synvolcanic gabbro of the Euclid Lake intrusion.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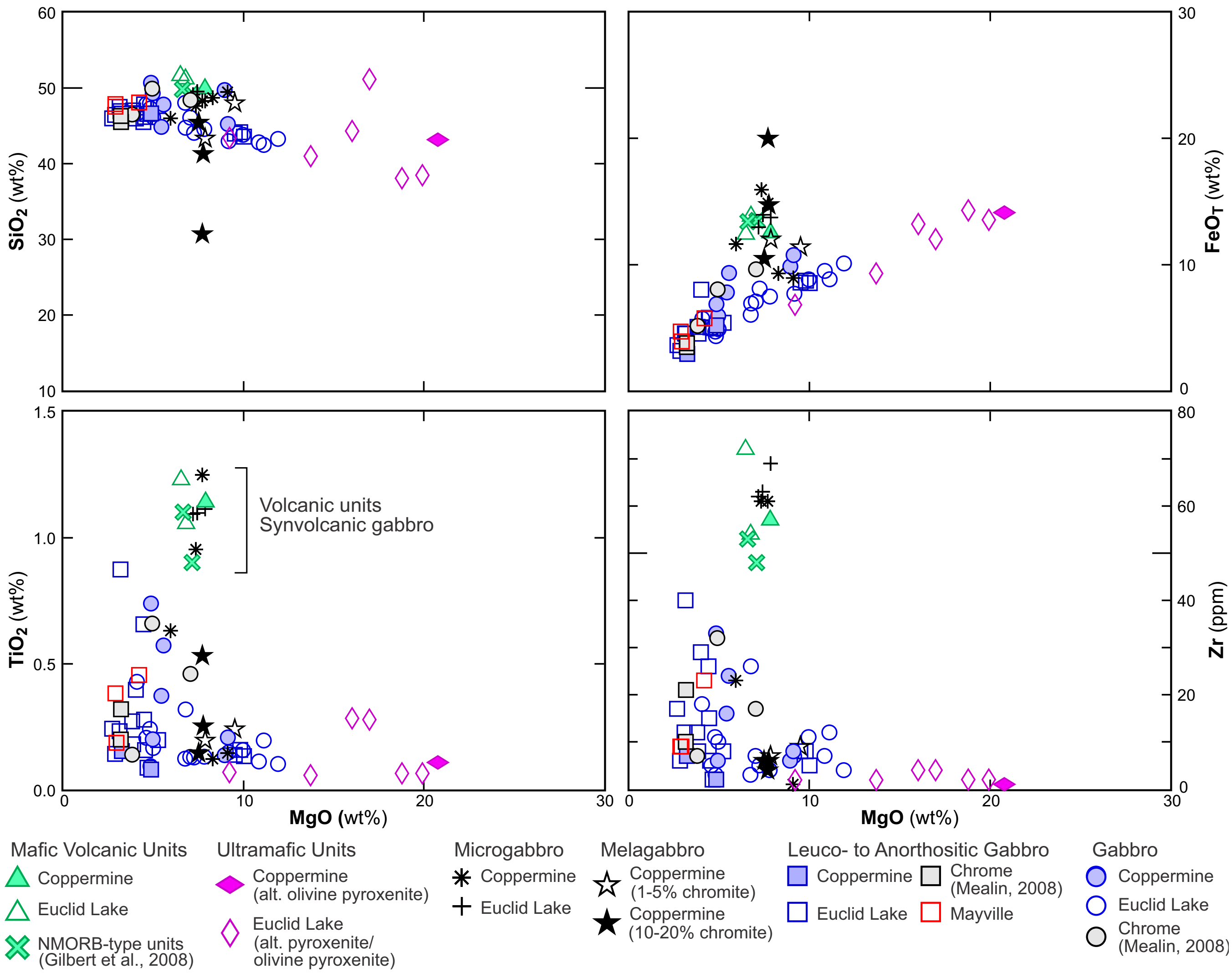

Figure 4. Whole-rock SiO_2, FeO_T, TiO_2, and Zr versus MgO contents for the main rock units from the Coppermine Bay and Euclid Lake intrusions. Chrome property data are from Mealin (2008) and the mean values of the Northern and Southern MORB-type units are from Gilbert et al. (2008).

ilar to gabbroic equivalents in the Coppermine Bay, BRS, and Mayville intrusions (Fig. 3a,d,f, respectively). The units consist mainly of calcic plagioclase (Fig. 2) and magnesiohornblende assemblage with traces of chlorite and ilmenite. The MgO, SiO_2, FeO_T, TiO_2, and Zr contents of these gabbroic phases are quite similar and comparable to those obtained for equivalent rock units from the Coppermine Bay intrusion and the Chrome property (Fig. 4). The REE profiles have a shallow negative slope from La to Nd and are relatively flat from Gd to Lu. Positive Eu anomalies are conspicuous for most samples (Fig. 5b).

Mafic volcanic rocks and subordinate synvolcanic gabbro were recognized at the basal (footwall) contact of the Euclid Lake intrusion (Bécu et al, 2013). The mafic volcanic rocks are typically dark grey and aphanitic to fine-grained, whereas the synvolcanic gabbro unit is fine- to medium-grained, and exhibits a salt-and-pepper texture in drill core in which light-coloured plagioclase (Fig. 2) contrasts with darker magnesiohornblende (Fig. 3h) with traces of apatite and ilmenite. This mineral assemblage is identical to that observed in the mafic volcanic rocks except for grain size and texture. Both the mafic volcanic rocks and synvolcanic gabbro have very similar MgO, SiO_2, FeO_T, TiO_2, and Zr contents (Fig. 4) as well as REE profiles. Their composition is also very similar to the composition of the Northern and Southern MORB-type formations within the BRGB as defined in Gilbert et al. (2008).

Mayville Intrusion

The Mayville intrusion is an east-trending, mafic-ultramafic body, approximately 10.5 km long and up to 1.5 km wide that hosts significant Cu-Ni resources and PGE-Cr occurrences. It is a mafic-dominated body that has been subdivided into a lower heterolithic breccia zone (melagabbro and pyroxenite with anorthosite and leucogabbro fragments) and an upper leucogabbro to anorthosite zone mainly consisting of leucogabbro, anorthositic gabbro, and anorthosite (e.g. Peck et al., 1999, 2002; Yang et al., 2012). The leucogabbroic to anorthositic rocks are medium-grained and typically contain plagioclase megacrysts (3–5 cm in diameter). These rocks, which are referred to as "golf-ball" leucogabbro/anorthosite, are texturally comparable to leucogabbroic to anorthositic rocks in other BRGB mafic-ultramafic intrusions (Fig. 3f). As observed in the Coppermine Bay and Euclid Lake intrusions, these gabbroic units are composed essentially of a plagioclase and hornblende assemblage with minor chlorite, epidote, and traces of biotite and ilmenite. Representative samples of the Mayville intrusion exhibit similar contents of MgO, SiO_2, FeO_T, TiO_2, and Zr and display similar REE profiles to those of the Chrome property gabbro as well as some of the Coppermine Bay and Euclid Lake intrusions (Figs. 4, 5). They results are also comparable to those obtained by Makie (2003) for gabbroic to anorthositic units from the heterolithic breccia zone.

GEOCHRONOLOGY

Geochronological investigations in this study include dating a leucogabbro xenolith sampled from the heterolithic breccia zone in the Mayville intrusion, which yielded a U-Pb isotope dilution thermal ionization mass spectrometry (ID-TIMS) zircon age of 2742.8 ±0.8 Ma, which is interpreted as the crystallization age for the intrusion (Houlé et al., 2013). This result is identical within error to the 2743.0 ±0.5 Ma age for a BRS leucogabbro from the Chrome property (Scoates and Scoates, 2013). Preliminary U-Pb ID-TIMS zircon ages from Coppermine Bay and Euclid Lake leucogabbroic rocks also suggest crystallization ages of 2743 Ma (McNicoll, unpubl. data).

DISCUSSION

Mafic rocks from mafic-ultramafic intrusions across the BRGB possess similar textural, petrological, and geochemical characteristics. This similarity is especially noticeable in outcrop textures of gabbroic to anorthositic rocks from the Coppermine Bay, Chrome, Maskwa-Dumbarton, Bird Lake, Euclid Lake, and Mayville intrusions (Fig. 3a–f). These units all consist of a calcic plagioclase and magnesiohornblende assemblage with minor chlorite-biotite-ilmenite. Their MgO, SiO_2, FeO_T, TiO_2, and Zr contents, as well as their REE profiles, are similar and suggest a probable magmatic affinity among these intrusions. These observations are in agreement with recently obtained U-Pb geochronological data and support a proposed linkage between mafic-ultramafic intrusions found in both arms of the BRGB. These intrusions are interpreted to

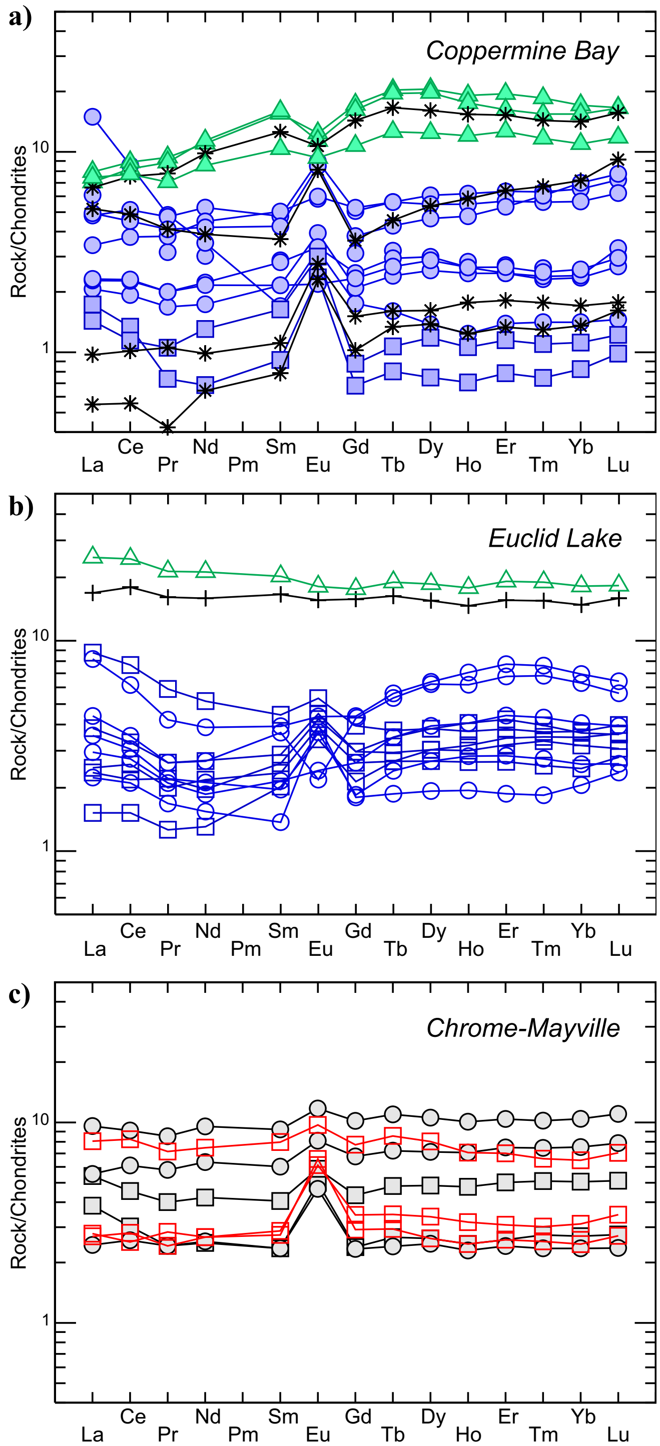

Figure 5. Chondrite-normalized rare earth element diagrams for representative gabbroic and volcanic rock units from **(a)** Coppermine Bay and **(b)** Euclid Lake intrusions. Data presented in **(c)** for the Chrome property (Mealin, 2008) and the Mayville intrusion (this study) are shown for comparison. Normalizing values are from Sun and McDonough (1989).

have formed as a result of an extensive single Neoarchean magmatic event at ca. 2743 Ma, identified as the Bird River intrusive suite (Houlé et al., 2013, 2015). This also supports previous conclusions of a potential connection between both arms of the BRGB,

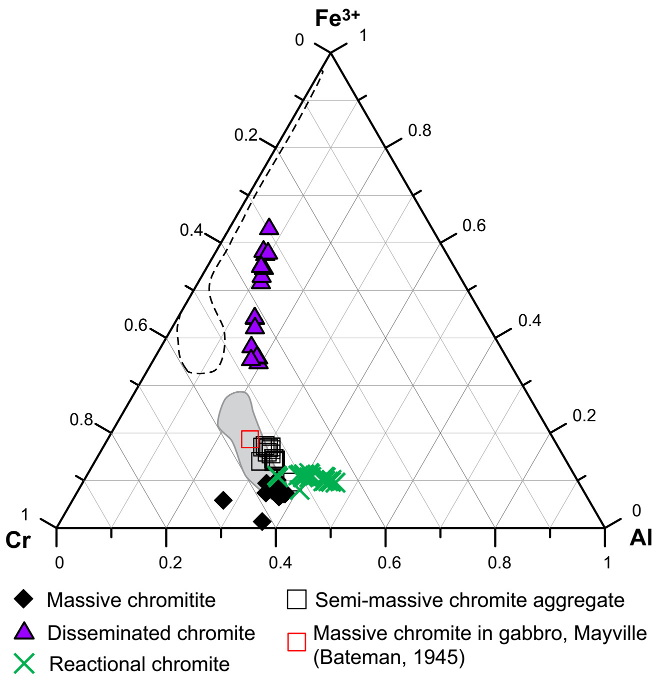

Figure 6. Chromite composition from the Mayville intrusion's E-Ext stripped outcrop, located in the northern arm of the BRGB. Shaded and dashed-line areas correspond to core and rim compositions respectively from Bird River Sill chromite occurrences (data from Barnes and Roeder, 2001; and this study).

and that mineral endowment of mafic-ultramafic intrusions might be linked. For example, a massive chromite sample hosted by gabbro from the Mayville intrusion (Bateman, 1945), as well as massive chromitite and semi-massive chromite aggregates from a chromite-bearing pyroxenite, exhibit mineral compositions similar to BRS-hosted chromite (Fig. 6). These observations support a common magmatic source for the Mayville and BRS intrusions located in the northern and southern arms of the belt, respectively.

The recognition of mafic volcanic rocks in the footwall of the Euclid Lake intrusion and their geochemical similarities with the Northern and Southern MORB-type formations in the southern arm of the BRGB infer an analogous geological setting to BRS. The presence of gabbroic rocks stratigraphically below the pyroxenite unit raises questions as to whether structural and/or complex magmatic process produced the magmatic sequence observed within the Euclid Lake intrusion (Bécu et al., 2013).

Geochemical investigations highlight that TiO_2 and Zr contents for intrusive anorthositic to gabbroic units are noticeably lower than those of mafic volcanic rocks. Similarly REE profiles for intrusive anorthositic to gabbroic units are much less REE enriched than those of mafic volcanic rocks. Although discrimination between these units is usually fairly straightforward in the field, textural criteria are not always adequate for defining microgabbroic units. Geochemistry can thus be used as a tool to help distinguish gabbro potentially related to the Bird River magmatic event from synvolcanic gabbro (Figs. 4, 5). A difference was also noted in the An content of plagioclase for a Coppermine Bay microgabbro (Fig. 3). The sample was interpreted to be of "Bird River magmatic affinity" based on low TiO_2 and Zr contents and a REE profile similar to anorthositic to gabbroic units, as well as distinctive anorthite indexes compared to those of plagioclase from a mafic volcanic unit of the Euclid Lake area. Ongoing investigations indicate that amphibole chemistry could also assist in the distinction between Bird River intrusive and volcanic-related rocks. Despite the relatively small dataset, these observed geochemical distinctions could prove to be useful in discriminating Bird River magmatic event-related mafic units from volcanic-related gabbro.

IMPLICATIONS FOR EXPLORATION

Results from this study suggest that the Coppermine Bay intrusion exhibits textural, petrographic, and geochemical characteristics that are similar to the Euclid Lake intrusion, and furthermore that both intrusions are comparable to the Mayville intrusion, supporting their proposed petrogenetic linkage. These observations, combined with recently obtained U-Pb ages, support the existence of a widespread Bird River magmatic event throughout the BRGB, as proposed by Houlé et al. (2013). Similar mineralization styles among the Coppermine Bay, Mayville, Euclid Lake, and other mafic-ultramafic intrusions, also strongly suggests that the potential for Ni-Cu-PGE-Cr mineralization extends well beyond the traditionally explored areas within the BRS and the Mayville intrusions.

Geochemical signatures, as well as mineral chemistry (plagioclase and amphibole), could be useful discrimination tools between Bird River magmatic event-related units and volcanic units. This could provide exploration tools to vector towards more prospective and fertile intrusions in the BRGB, especially in volcanic-dominated areas such as the Cat Creek area south of the Mayville intrusion.

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