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

Petrogenesis of the ferrogabbroic intrusions and associated Fe-Ti-V-(P) mineralization within the McFaulds greenstone belt, Superior Province, northern Ontario

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ABSTRACT

The Thunderbird and Butler intrusions of the McFaulds Lake greenstone belt ("Ring of Fire") were studied to determine petrogenesis and associated Fe-Ti-V-(P) mineralization. These intrusions are characterized by variably well layered gabbro-anorthosite intrusions with abundant Fe-Ti oxides, broadly termed ferrogabbro. The layers are composed of partial to complete cycles that comprise basal massive oxide (magnetite-ilmenite), which grade into semi-massive oxide units, followed by oxide-rich pyroxenite/melagabbro/gabbro, oxide-poor melagabbro/gabbro/leucogabbro, and topped with oxide-free leucogabbro/anorthosite. The cycles range from centimetres to metres in thickness and define the well layered portions of the intrusions that typically exhibit sharp upper and lower contacts with gradational internal contacts. Conversely, the intrusions contain broad intervals of disseminated magnetite-ilmenite (2–5%) hosted in melagabbro/gabbro/leucogabbro/anorthosite, which range in thickness from metres to tens of metres. The layering and textures observed within the ferrogabbro units are thought to be dominantly produced by convection currents with intermittent periods of quiescence.

The ferrogabbro intrusions are characterized by gently sloping LREE and flat HREE patterns. This geochemical signature most closely corresponds to an E-MORB source that is thought to have been the result of interaction of a mnalte plume with MORB-like mantle under the McFaulds Lake area. This plume-related magma is thought to have undergone differentiation, resulting in the abundant Cr-Ni-Cu-PGE-bearing ultramafic and evolved Fe-Ti-rich mafic suites in the McFaulds area. Additionally, the plume may have resulted in a thinned lithosphere and produced the coeval VMS occurrences.

Also studied is the potential application of the TiO_2/V_2O_5 ratio for the identification of prospective vanadium mineralization and to aid in the determination of magmatic stratigraphy.

INTRODUCTION

The McFaulds Lake greenstone belt (MLGB), commonly known as the "Ring of Fire", has been the site of base and precious metal exploration over the past decade. This region, located in Ontario's far north, was recognized as an underexplored greenstone belt with the discovery of the McFaulds Lake VMS occurrences in 2002 (Metsaranta and Houlé, 2011, 2012). Exploration in the area quickly resulted in the discovery of numerous chromite deposits (e.g. Black Thor, Black Label, Big Daddy, Black Creek, Black Horse, and Blackbirds), one Ni-Cu-PGE deposit (Eagle's Nest), and numerous Fe-Ti-V-(P) occurrence (Metsaranta et al., 2015).

Although most of the emphasis has been placed on Cr and Ni-Cu-PGE deposits, the Fe-Ti-V-(P) mineralized intrusions have received little attention and this study was initiated in response to this lack of knowledge on the mafic-dominated intrusions that host this style of mineralization. The main goal of this research project was to investigate the petrogenesis of the Fe-Ti-V-(P) mineralization within the Thunderbird, Butler West, and Butler East intrusions in the McFaulds Lake greenstone belt (Fig. 1).

RESEARCH METHODS

In the course of this project, several weeks of fieldwork was completed on the Butler Lake and the Thunderbird properties. Fifteen diamond drillholes were selected and characterized to produce detailed stratigraphic logs (10 drillholes at Butler and 5 drillholes at Thunderbird) of the intrusions. Petrographic work was conducted on 143 samples, 68 from the Thunderbird intrusion and 75 from the Butler (East and West) intrusions, to investigate their textural and lithological characteristics. Further characterization of the silicate and oxide minerals was conducted using a CAMECA SX-100 elec-

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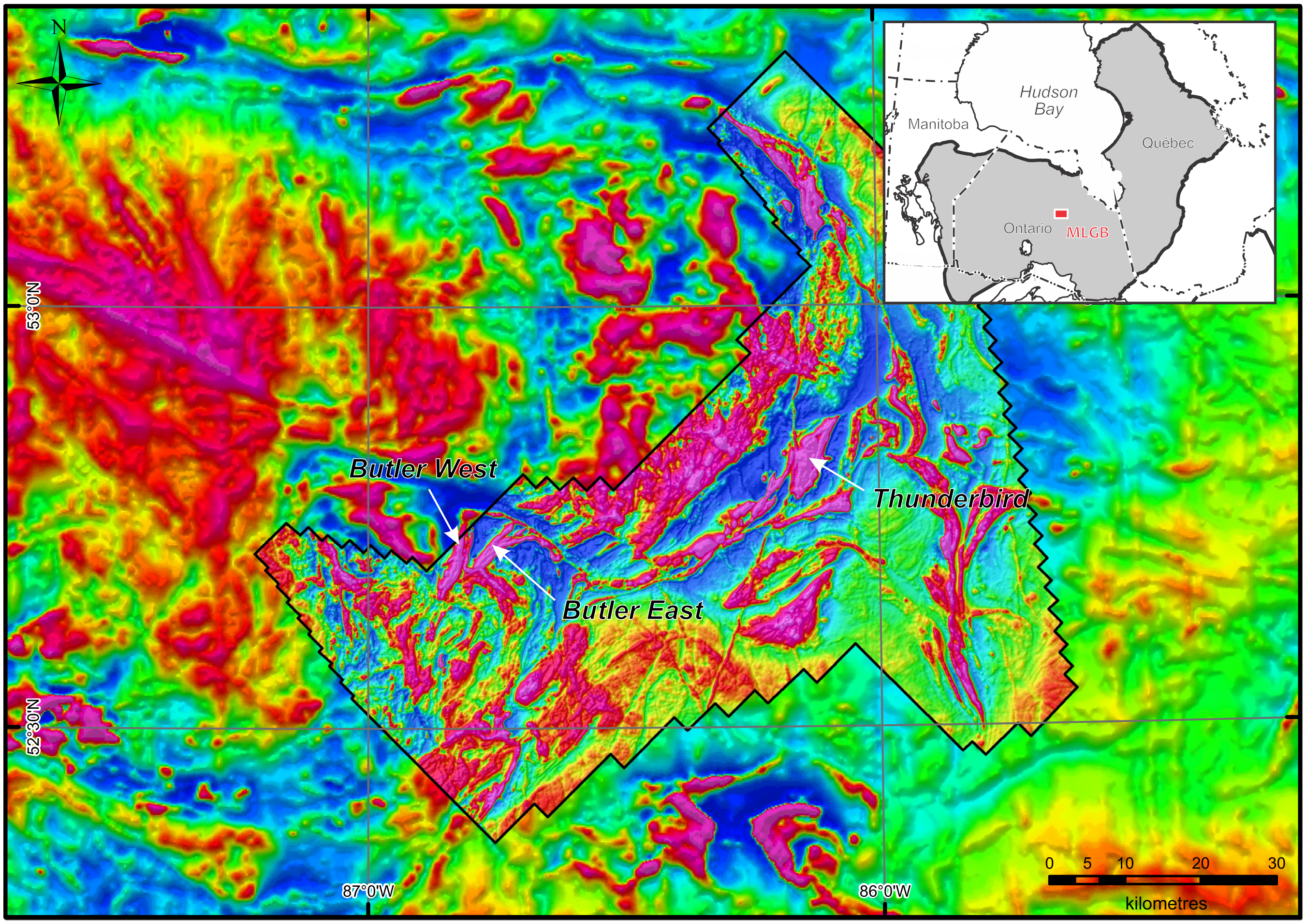

Figure 1. Total residual magnetic field showing the location of the Butler West, Butler East, and Thunderbird intrusions in the McFaulds Lake area. Detailed magnetic data are from the Ontario Geological Survey–Geological Survey of Canada (2011) and the regional data are from the Geoscience Data Repository for geophysical data of Natural Resources Canada, which can be access at http://gdr.agg.nrcan.gc.ca/gdrdap/dap/search-eng.php.

tron microprobe analyzer (EMPA) at the Ontario Geoscience Laboratories (Geo Labs). A total of 100 samples of representative drill core were selected for whole-rock and trace element geochemistry, 46 samples from Thunderbird intrusion and 54 from the Butler intrusions, to characterize the lithologies and determine possible magmatic stratigraphy (Kuzmich et al., 2015). The reader is also referred to Kuzmich et al. (2013) and Kuzmich (2014) for more detailed aspects of this project, including the analytical parameters and procedures used in this study.

RESULTS

Lithofacies

The Butler and Thunderbird intrusions are part of a mafic-dominated "ferrogabbro" subsuite of the Neoarchean Ring of Fire Intrusive Suite (RoFIS) and represent some of the best defined ferrogabbroic intrusions within the McFaulds Lake greenstone belt. The the ferrogabbroic subsuite are described as mafic-dominated intrusions that exhibit an excess of iron oxides and/or an iron and titanium geochemical enrichment (Metsaranta and Houlé, 2011; Metsaranta et al., 2015). These intrusions are characterized by a suite of well layered magnetite-ilmenite-rich rocks that are dominantly composed of gabbroic to anorthositic (Fig. 2a,b) units with lesser stratigraphically conformable units composed of massive magnetite-ilmenite (Fig. 2c). Rare pegmatitic units have been also observed within these intrusions but are better exposed in the Butler East intrusion (Fig. 2d). These pegmatitic units are bound by gradational contacts and are composed of mineralogy identical to the ferrogabbro units but with plagioclase and pyroxene grains in excess of 3 cm. The Fe-Ti oxides are variably mineralized with vanadium but generally contain low chromium contents (magnetite up to 2.45 wt% V_2O_5 and 0.99 wt% Cr_2O_3; ilmenite up to 0.57 wt% V_2O_5). The massive and semi-massive oxide layers range in thickness from centimetres to metres (Fig. 2e) and occur typically as basal members of repeated cycles characterized by sharp lower contacts that grade upwards into oxide-rich

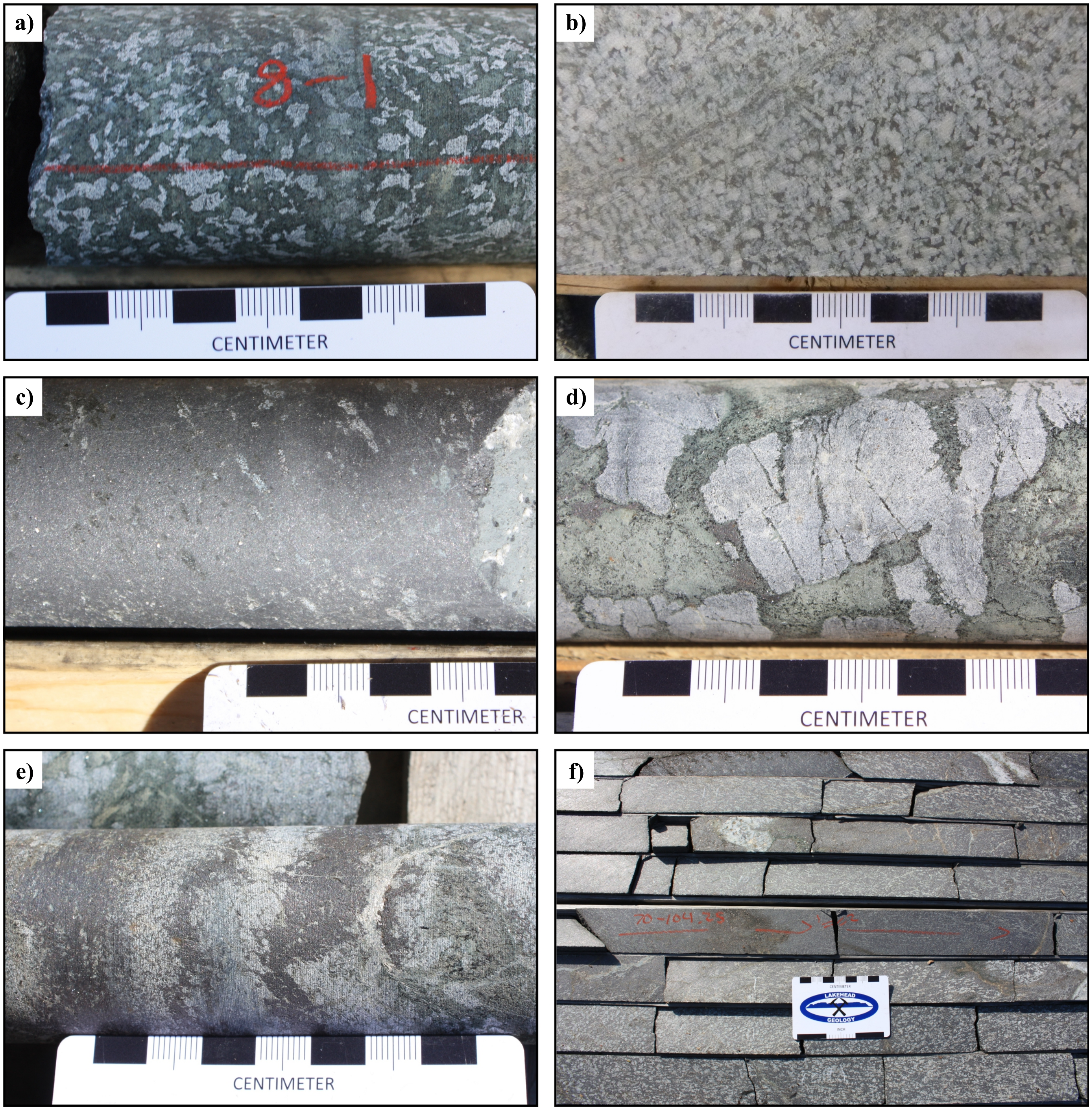

Figure 2. Representative lithofacies within the ferrograbroic subsuite in the McFaulds Lake greenstone belt. **a)** Medium-grained gabbro from the Butler West intrusion (sample BP11-V08). **b)** Medium-grained anorthosite from the Thunderbird intrusion (sample NOT-11-2G25). **c)** Fine-grained massive oxide unit from the Butler West intrusion (sample BP11-V08). **d)** Pegmatitic gabbro with fractured plagioclase from Butler West intrusion (sample MN08-117). **e)** Thinly layered massive oxides and anorthosite from the Butler West intrusion (sample MN08-117). **f)** Semi-massive to massive oxide layers from the Butler East intrusion (sample MN08-70).

pyroxenite, followed by oxide-bearing leucogabbro and/or anorthosite (Fig. 2f).

Petrography

The majority of the ferrogabbroic intrusions are variably composed of medium-grained pyroxene, amphibole, plagioclase, magnetite, and ilmenite. However, the primary silicate mineralogy of these intrusions has largely been replaced by secondary Fe-rich and Fe-poor chlorite, amphibole, clinozoisite, and epidote with accessory titanite, garnet, quartz, and/or potassium feldspar. Primary plagioclase often exhibits strong deformation features (e.g. deformation twins, subgrain boundaries) and as a result the anorthite content, deter-

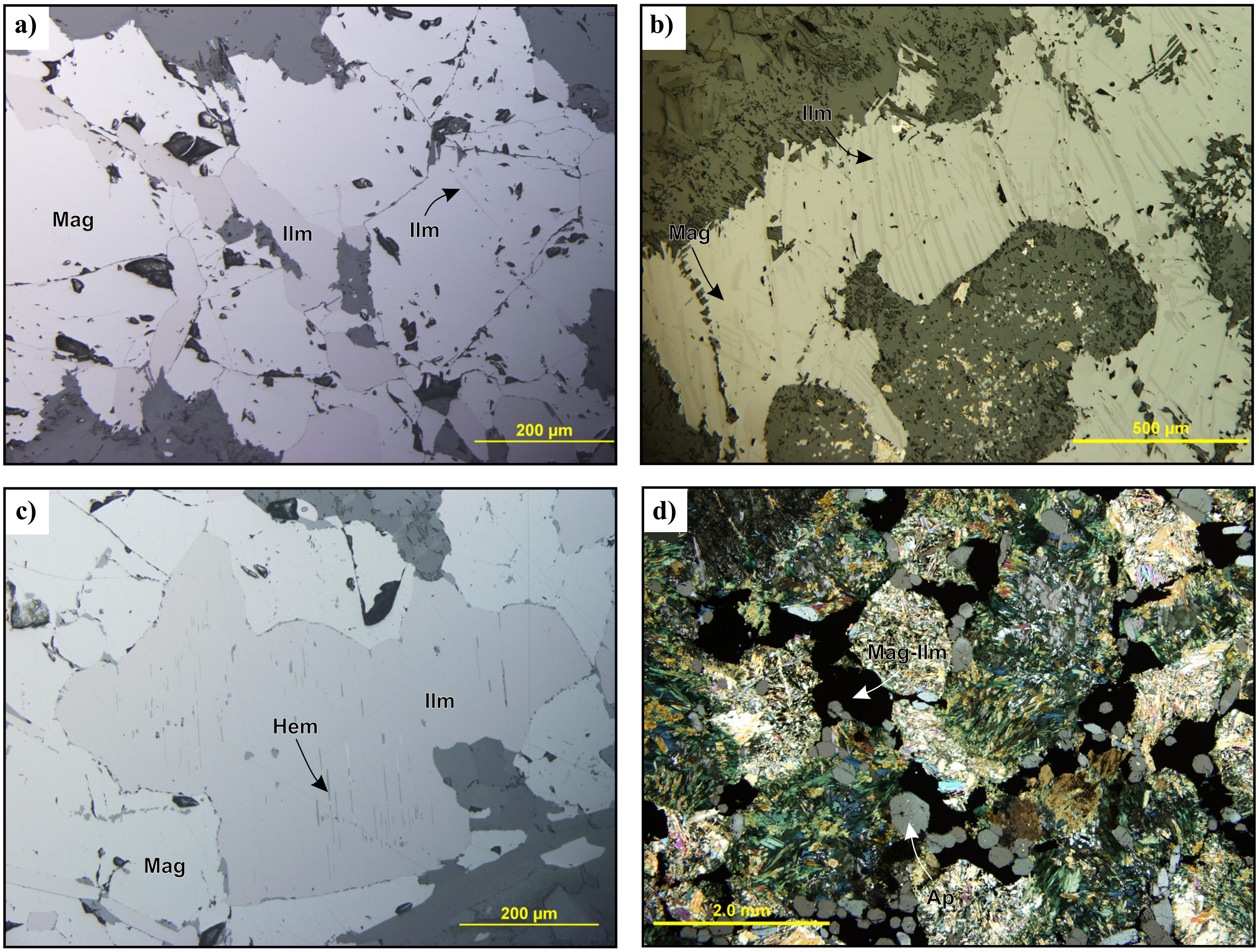

Figure 3. Representative photomicrographs displaying Fe-Ti-V-(P) mineralization textures. **a)** Granular ilmenite with minor ilmenite exsolution within magnetite (reflected light, XPL: sample MN10-117, Butler West intrusion). **b)** Ilmenite exsolution within evolved magnetite (reflected light, XPL: sample NOT-11-2G46, Thunderbird intrusion). **c)** Hematite exsolution within primary ilmenite (reflected light, XPL: sample BP11-V01, Butler West intrusion). **d)** Apatite-oxide mineralization within melagabbro (transmitted light, XPL: sample NOT-11-2G46, Thunderbird intrusion). Abbreviation: Ap = apatite; Hem = hematite; Ilm = ilmenite; Mag = magnetite; XPL = cross-polarized.

minations using the Michel-Lévy method are generally unreliable. Pyroxene grains, when present, are typically clinopyroxene with rare orthopyroxene and are partially to completely replaced by blue/green amphibole grains, which rim the pyroxene. Magnetite grains are typically fine- to medium-grained and display variable abundances of ilmenite exsolution and textures. Magnetite, which is interpreted to have crystallized within the basal portion of these intrusions, generally contains only minor (0–5%), thin (<3 µm) ilmenite lamellae and/or very fine-grained granular ilmenite (Fig. 3a), in stark contrast to the magnetite within the highly evolved upper member of these intrusions, which is characterized by the presence of thick (5–15 µm), abundant (20–30%) ilmenite lamella (Fig. 3b). Primary ilmenite (i.e. not a product of oxy-exsolution) displays less variation than the ilmenite that has exsolved from magnetite. Primary ilmenite generally occurs as subhedral to euhedral tabular fine- to medium-grained crystals with trace amounts of very fine-grained (<2 µm) hematite exsolutions, which is only observed within the upper portions of the intrusions (Fig. 3c). Apatite is a rare mineral and only occurs in significant concentrations (1–4.5%) in the most evolved portion of the Thunderbird intrusion. Apatite occurs as fine-grained euhedral clear prismatic grains associated with disseminated to net-textured fine-grained anhedral magnetite-ilmenite (Fig. 3d).

Mineral Geochemistry

Magnetite and ilmenite grains lack any apparent compositional zoning. Magnetite grains are V_2O_3-rich (<2.46%) but poor in TiO_2 (<1.42%) and Cr_2O_3 (<0.99%) and display patterns of increasing TiO_2, V_2O_5, Al_2O_3, and Cr_2O_3 with decreasing Fe_2O_3/FeO contents. Magnetite has very low concentrations of

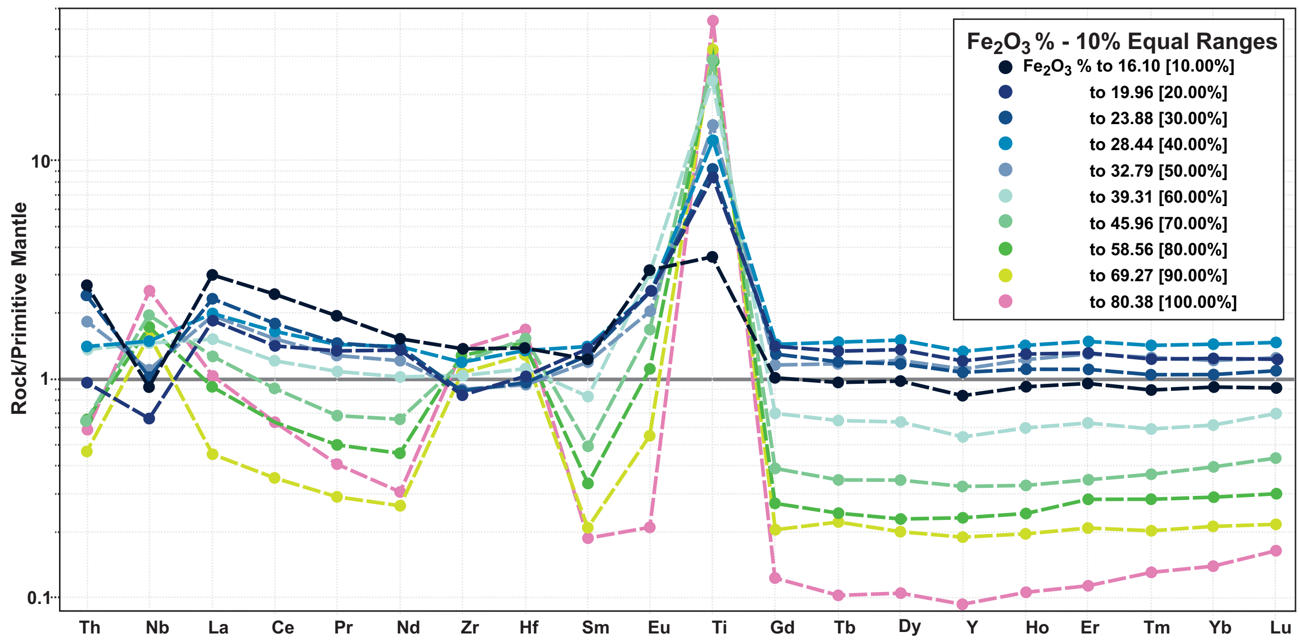

Figure 4. Primitive-mantle normalized plot for the Butler West, Butler East, and Thunderbird intrusions grouped according to weight % Fe_2O_3. Normalizing values are from Sun and McDonough (1989).

SiO_2, Al_2O_3, MgO, MnO, CoO, NiO, CuO, and ZnO. Ilmenite grains contain significant MnO (<1.82%), V_2O_5 (<0.57%), and MgO (<0.41%) with only minor SiO_2, Al_2O_3, Cr_2O_3, Nb_2O_3, CoO, NiO, CuO, and ZnO. Primary magnetite-ilmenite pairs have been used to calculate the conditions of crystallization based on the method proposed by Spencer and Lindsley (1981), although large variations in data were observed, the approximate temperature of crystallization has been calculated as 400–500°C (Kuzmich, 2014). However, the calculated temperatures obtained are too low to represent crystallization of a gabbroic melt, which is suggested to be ~1100°C (Toplis and Carroll, 1995), and are interpreted instead to represent the conditions of oxy-exsolution from a primary ulvöspinel-magnetite solid solution (Kuzmich, 2014). Magnetite and ilmenite grains also display lower concentrations of highly compatible elements (e.g. V, Cr) with increasing stratigraphic height.

The study of silicate minerals was focused on the identification of end-member minerals. Pyroxene grains were largely composed of augite and pigeonite with lesser ferrosilite, enstatite, and/or wollastonite. Pyroxene grains have been partially to completely replaced by amphibole, which is dominantly composed of hornblende and actinolite with lesser pargasite. Plagioclase compositions display a trend of decreasing anorthite content with increased stratigraphic height. Basal plagioclase generally ranges from 53 to 67% An (labradorite) with a few analysis as high as 86% An (bytownite), whereas more evolved units contain plagioclase that is generally restricted to 37–52% An (andesine dominate).

Whole-Rock and Trace Element Geochemistry

The ferrogabbroic rocks display a large range of major element compositions due to the large variability in modal mineralogy. However, the major elements display positive trends of increasing SiO_2 contents with increasing Al_2O_3, CaO, MgO, and Na_2O and decreasing Fe_2O_3, MnO, V_2O_5, and TiO_2. Additionally, higher Fe_2O_3 contents (which may be used to estimate the amount of magnetite in the sample) correlate with increased TiO_2, V_2O_5, Cr, Ni, Co, and Zn contents.

Trace element diagrams display similar patterns between the Thunderbird and Butler intrusions (Fig. 4). The plots are characterized by slightly depleted LREE, flat HREE patterns, and positive Ti and weak negative Y anomalies. These patterns display a strong dependence on the concentration of magnetite-ilmenite within each sample (Fig. 4). Samples with high concentrations of Fe-Ti oxides (e.g. massive oxides) generally exhibit positive Nb, Zr, Hf, and Ti anomalies, whereas the oxide-free samples (e.g. gabbro) display negative Nb, Zr, and Hf anomalies. Additionally, oxide-rich samples contain lower trace element contents by an order of magnitude on average than the oxide-free samples but contain similar high field strength element (HFSE) contents. Apatite-bearing units display distinctly different trace element patterns that are characterized by one to two orders of magnitude higher concentrations of trace elements than the average ferrogabbroic rocks.

DISCUSSION

Formation of Layering

Igneous layering within the ferrogabbroic rocks is a distinct feature observed throughout each intrusion. The most pronounced form of layering within these intrusions is composed of repeated partial to complete sequences characterized by sharp lower and upper contacts with gradational internal contacts. These cycles are composed of basal massive oxides that grade upwards into semi-massive oxides, followed by oxide-rich pyroxenite/melagabbro/gabbro, oxide-poor melagabbro/gabbro/leucogabbro/anorthosite, and topped with oxide-free gabbro/leucogabbro/anorthosite. These layers are interpreted to have formed through intermittent convection currents (Kuzmich, 2014) similar to what it has been proposed by Naslund et al. (1991) for the Skaergaard intrusion. Each convective cycle supplied the crystallizing front with dense, Fe-Ti oxides and in periods of quiescence the magma deposited crystals/minerals in order of decreasing density.

Layers of stratigraphically conformable pegmatitic units composed of oxide-bearing ferrogabbro occur within all intrusions, but are most prevalent within the Butler West intrusion. These units display gradational contacts and are mineralogically identical to the surrounding medium-grained ferrogabbro. These layers are thought to have formed in the presences of relatively volatile-rich phases and possibly reflect introduced fluids from the country rocks or from the migration of fluid dissolves in the intercumulus melt during the cooling of the cumulate pile within the intrusion (e.g. Nicholson and Mathez, 1991; Boudreau, 1999).

Petrogenesis of Butler and Thunderbird Intrusions

The Butler and Thunderbird intrusions represent three of numerous gabbroic intrusions currently recognized within the McFaulds Lake area that are characterized by extreme degrees of iron enrichment (Metsaranta et al., 2015). These intrusions are proposed by Kuzmich (2014) to have originated from a mantle plume source that underplated the McFaulds Lake greenstone belt. The plume-related magmas likely differentiated into a primitive ultramafic portion and an evolved mafic portion, similar to what has been proposed for the Emeishan plume (Zhou et al., 2008). The evolved mafic magma would exist as a reduced, anhydrous melt that was variably contaminated by the depleted mantle, as suggested by enriched mid-ocean ridge basalt (E-MORB) trace element patterns.

The plume-sourced mafic melt underwent a two-stage evolution, the first of which is characterized by a system that was closed to oxygen, anhydrous, reduced, and underwent crystallization of Fe-poor mineral phases (e.g. olivine, plagioclase), which resulted in an Fe-rich residual magma. The second stage is characterized by shallow emplacement within a system partially open to oxygen, which allowed the magma to initiate

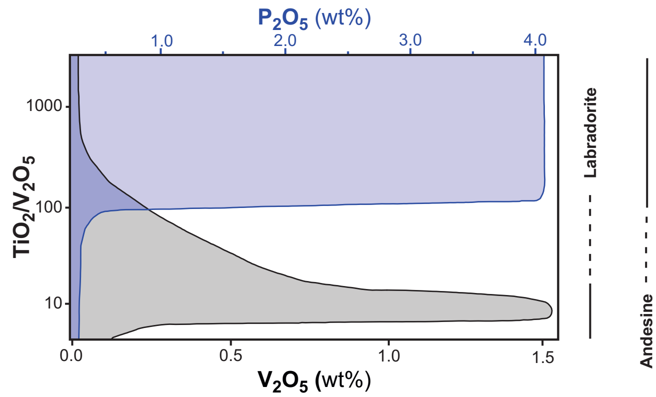

Figure 5. Binary plot of TiO_2/V_2O_5 ratio versus V_2O_5 (bottom axis) and versus P_2O_5 (top axis), which is use as proxy for V-rich magnetite and for apatite, respectively, in the Butler and Thunderbird intrusions (Kuzmich, 2014).

the crystallization of Fe-Ti oxides. The onset of magnetite-ilmenite crystallization would reverse the evolution from Fe-Ti enrichment to a system that would follow an anorthositic-granitic evolutionary trend. Kuzmich (2014) suggested the same mantle plume that generated the ferrogabbroic intrusions also produced the voluminous Cr-Ni-PGE-mineralized ultramafic intrusion (e.g. Eagle's Nest, Black Thor) and resulted in a thinned lithosphere that facilitated the coeval Cu-Zn VMS occurrences at ca. 2735 Ma (Mungall et al., 2010).

IMPLICATIONS FOR EXPLORATION

Through this study on the Fe-Ti-V-(P) mineralized ferrogabbroic intrusions in the McFaulds Lake greenstone belt, variations in the TiO_2/V_2O_5 whole rock ratio have demonstrated the potential to be a useful tool in the interpretation of stratigraphy and to aid in the determination of prospective vanadium and/or possible phosphorous horizons (Fig. 5). The ratio is interpreted to increase during magmatic evolution and, with large datasets, can be used to interpret stratigraphic way-up. The use of the TiO_2/V_2O_5 ratio is particularly of interest due to the resistant nature of the host oxide minerals (magnetite and ilmenite) to metamorphism and the minerals can be analysed at relatively low cost (e.g. X-ray fluorescence) and are independent of the bulk silicate composition.

The maximum vanadium potential for the Butler and Thunderbird intrusions, based on a data set of >2600 samples (data provided by from MacDonald Mines Ltd. and Noront Resources Ltd.), can be estimated using Figure 5. Samples that have TiO_2/V_2O_5 values of ~8 to 12 display the richest vanadium-bearing magnetite and therefore the highest potential for economic concentrations in massive and semi-massive oxide layers. The vanadium potential exponentially decreases as the TiO_2/V_2O_5 ratio increases; for example, a ratio of ~40 is proposed to represent one third of the potential as values in the ~8 to 12 range, and ratios of >500 display no potential for vanadium mineralization, even within massive oxide units. Conversely, all apatite mineralization (<4 wt% P_2O_5) is associated with higher TiO_2/V_2O_5 ratios (>100), which may represent Fe-Ti-P-rich melts (nelsonite).

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