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

The petrology, mineralization, and regional context of the Thunder mafic to ultramafic intrusion, Midcontinent Rift, Thunder Bay, Ontario

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ABSTRACT

The 1108 Ma Thunder mafic to ultramafic intrusion is a small, 800 x 100 x 500 m, Cu-PGE mineralized body, located on the outskirts of Thunder Bay, Ontario. It is associated with the early magmatic stages of the Midcontinent Rift based on geochemical similarities to mafic and ultramafic rocks of the Nipigon Embayment and a $^{207}Pb/^{206}Pb$ zircon age of 1108.0 ± 1.0 Ma. The Thunder intrusion is similar to other known mineralized early-rift Midcontinent Rift intrusions; however, it is the only known occurrence of the Midcontinent Rift hosted in an Archean greenstone belt (Shebandowan). Major textural and geochemical differences can be used to subdivide the intrusion into a lower mafic to ultramafic unit and an upper gabbroic unit; the similar trace and rare earth element ratios of the two units suggest a single magmatic pulse that has undergone subsequent fractional crystallization and related cumulate phase layering. The estimated parental composition of the Thunder intrusion has a Mg# (MgO/(MgO+FeO_{Tot}), mole%) of 57, which represents a more evolved magma than other early-rift mafic to ultramafic intrusions and may indicate multiple staging chambers during the ascent of the parent magma.

Trace and rare earth element patterns are consistent with a mantle plume ocean island basalt-like source but with high-Th concentrations and a negative Nb anomaly. The εNd_t values of the intrusion range between -0.7 and +1.0, with no trends indicative of progressive wall-rock contamination, whereas the $^{87}Sr/^{86}Sr_i$ ratios range from 0.70288 to 0.70611 and trend towards wall-rock values of between 0.70712 and 0.70873. The radiogenic Sm-Nd and Rb-Sr isotope signature is similar to the contamination trends of the Nipigon sills, which is interpreted to represent contamination by shallow-basin-filling sedimentary rocks.

Ni-Cu-PGE sulphide mineralization (20 m of 0.22 wt% Cu, 0.06 wt% Ni, 0.25 ppm Pt, and 0.29 ppm Pd) is hosted by feldspathic peridotite in the lower mafic to ultramafic unit adjacent to the footwall rock of the Thunder intrusion. Sulphides typically comprise 1 to 5 modal%, rarely up to 30 modal%, with textures ranging from medium- to fine-grained, disseminated, globular, and rarely net-textured. Pyrrhotite, chalcopyrite, and rare pentlandite, with common secondary marcasite-pyrite replacement, occur together with trace michenerite, kotulskite, merenskyite, sperrylite, hessite, electrum, and argentian pentlandite. Whole-rock geochemical data display fractionated Ni-Cu-PGE patterns with depletion of iridium subgroup relative to the platinum subgroup.

Sulphide $\delta^{34}S$ values from the Thunder intrusion range from -2.0 to +3.8‰ and are similar to values for the metavolcanic host rock, which range from -3.1 to +2.3‰. Two samples of the basal mineralization zone sulphides yield $\Delta^{33}S$ values of 0.066 and 0.122‰ and one sample of the metavolcanic wall rock yields 0.149‰. The $\delta^{34}S$ and $\Delta^{33}S$ values for the Thunder intrusion fall within range for rocks of typical upper mantle composition. The sulphur source is difficult to resolve. It appears to be of mantle origin as the wall-rock S isotope values and S/Se_{Tot} signature are similar to that of upper mantle; however, assimilation of crustal sulphur is also a possibility.

INTRODUCTION

The recent discovery (2002) of the high-grade Ni-Cu-PGE Eagle deposit in the Midcontinent Rift (MCR) in Michigan has stimulated exploration for small mafic to ultramafic intrusions hosting "conduit-type" mineralization across the Canada-United States border. More than six poorly exposed mineralized early-rift mafic to ultramafic intrusion have been discovered within the Lake Superior region, leading to considerable petrological research (e.g. Heggie, 2005; Hollings et al., 2007a,b; Ding et al., 2010; Foley, 2011; Goldner, 2011) and re-evaluation of the current MCR tectono-magmatic model (Heaman et al., 2007; Hollings et al., 2010; Miller and Nicholson, 2013). However, the small

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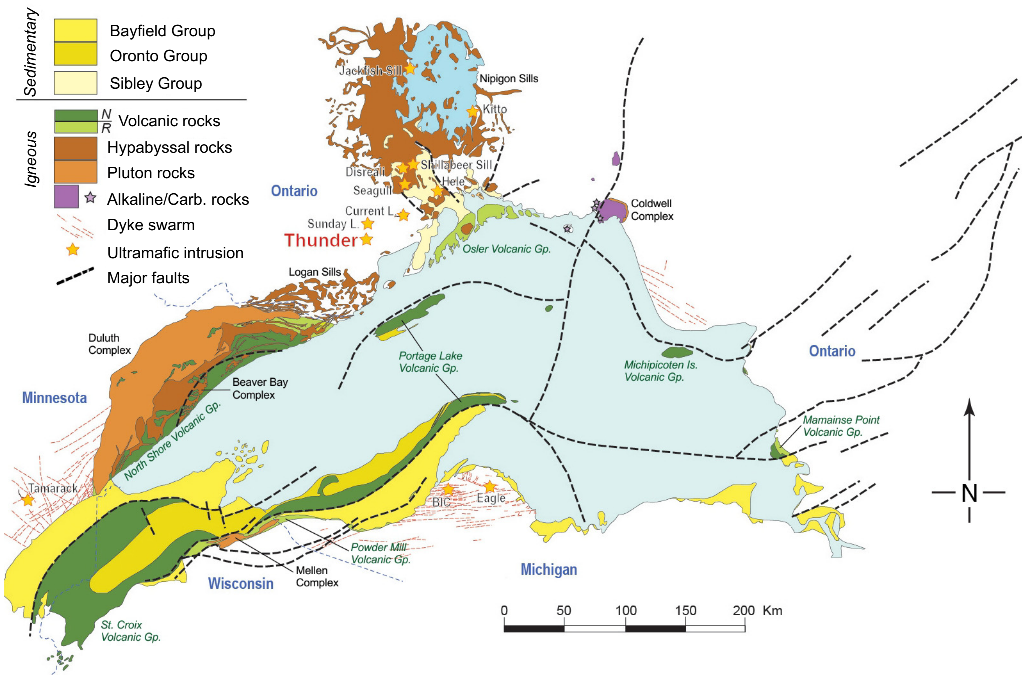

Figure 1. Present-day exposure of the Midcontinent Rift geology in the Lake Superior region. Labelled are the major volcanic and intrusive units. Indicated by the yellow stars are locations of the known ultramafic intrusions associated with the early magmatic stages of Midcontinent Rift evolution. Figure modified after Miller and Nicholson (2013).

size of these buried mineralized ultramafic intrusions makes them hard to detect, both on the ground and from regional magnetic survey maps.

The Thunder intrusion is a small, mineralized, mafic to ultramafic intrusion, which is located on the outskirts of the City of Thunder Bay (Fig. 1) and was explored by Rio Tinto (formerly Kennecott Canada Exploration Inc.) in 2005 and 2007 (Bidwell and Marino, 2007). Early investigations interpreted this intrusive body to be an early-rift occurrence based on geochemical similarities with the mafic to ultramafic intrusive units of the Nipigon Embayment (e.g. Hele intrusion and Shillabeer sill; Hollings et al., 2007a; D. Rossell, pers. comm., 2012). The Thunder intrusion is distinct from other mineralized early-rift intrusions in that it is the only known occurrence hosted by the metavolcanic and metasedimentary rocks of the Archean Shebandowan greenstone belt (Ames et al., 2012). Other early-rift intrusions north of the Canada-United States border, including Current Lake and Seagull, intrude the Archean Quetico metasedimentary subprovince and/or Mesoproterozoic Sibley Group sedimentary rocks (Heggie, 2005; MacTavish et al., 2013). South of the Canada-United States border, the Paleoproterozoic sedimentary rocks of the Animikie and Baraga basins (Ding et al., 2010; Foley, 2011; Goldner, 2011) host a number intrusions, such as Eagle, Bovine Igneous Complex, and Tamarack.

This report highlights the first author's (B.E. Trevisan) M.Sc. study (2014), which was a collaborative project between Lakehead University (LU), the Geological Survey of Canada (GSC), and the Ontario Geological Survey (OGS) as part of the Ni-Cu-PGE-Cr project, Targeted Geoscience Initiative-4 program (TGI-4; Ames et al., 2012). The main objective is to characterize the petrology, mineralization, and alteration footprint of the Thunder intrusion within the context of the MCR as a whole, in order to identify criteria for targeting buried mineralization (Fig. 1).

METHODOLOGY

Field work included geological mapping and re-logging of the seven diamond drillholes (DDH) intersecting the mineralized Thunder intrusion. A suite of 104 samples of representative lithology, mineralization, and alteration types were analysed for whole-rock geochemistry (OGS, in-kind contribution; Trevisan et al., 2015). A subset of samples was studied and analyzed using SEM (LU and GSC), electron microprobe (GSC), radiogenic Rb-Sr and Sm-Nd isotopes (Carleton University), S-isotopes (Indiana University), and geochronology (GSC). Most of the samples used for the analytical investigations were from DDH 07TH004, as it was determined to be the most stratigraphically complete representation of the Thunder intrusion and its wall rocks.

A 5 kg sample of a coarse (grain size ~1 cm) gabbroic phase of Thunder intrusion was prepared using standard methods of crushing and grinding, followed by density separations using a Wilfley table and heavy liquids (methylene iodide) to concentrate heavy minerals. Zircon and baddeleyite grains were selected after examination under a binocular microscope. The sample was analyzed by the isotope dilution-thermal ionization mass spectrometry (ID-TIMS) technique. Zircon grains were treated with the chemical abrasion method

(Mattinson, 2005) before being submitted for U-Pb chemical analysis. Baddleyeite grains were not subjected to any pre-dissolution treatment (neither chemical nor physical abrasion). Dissolution of both zircon and baddeleyite in a concentrated heavy fraction, extraction of U and Pb, and mass spectrometry followed the methods described in Parrish et al. (1987). Data reduction and numerical propagation of analytical uncertainties follow Roddick (1987). Analytical blanks for Pb were 1 pg. Results are presented in Table 1 with uncertainties reported at the 2σ level. The computer profram Isoplot v. 3.00 (Ludwig, 2003) was used to generate concordia plots and calculate weighted means. All ages quoted in the text and error ellipses on all concordia diagrams represent 2σ uncertainty level.

RESULTS AND SUMMARY

Geology of the Thunder Mafic to Ultramafic Intrusion

Field mapping showed the Thunder intrusion to be a mafic to ultramafic intrusion with a surface area of 800 x 1000 m (Fig. 2). The intrusion can be divided into two major lithological units: a lower mafic to ultramafic unit and an upper gabbroic unit. The country rocks include mafic to intermediate metavolcanic rocks of the Shebandowan greenstone belt. In addition, outcrops of a north-trending gabbroic dyke were identified east of the Thunder intrusion. The magnetic signature of an iron formation horizon can be traced with the aid of airborne geophysical data (OGS, 2003). No major structures were observed in the field surrounding the Thunder intrusion. Contact relationships between the Thunder intrusion and surrounding country rock were only rarely observed. The geological boundary of the Thunder intrusion was defined with the aid of airborne geophysical data, as there was generally a gap between outcrops of the Thunder intrusion and country rock (Fig. 2). A geological field guide is available for the area (Trevisan et al., 2013).

A simplified lithological cross-section of the Thunder intrusion was constructed along five drillholes that lie along a similar azimuth. This section suggests that the Thunder intrusion is <600 m total thickness with a steep southward dip (Fig. 3). Only the intrusion and the footwall rocks were intersected by drilling.

Petrology of the Thunder Intrusion

Primitive mantle-normalized profiles of the Thunder intrusion are characterized by light rare earth element enrichment and fractionated heavy rare earth element. The similar slope of the upper gabbroic unit and lower mafic to ultramafic unit primitive mantle-normalized profiles are consistent with a single magmatic pulse that has undergone subsequent fractional crystallization and related cumulate phase layering (Trevisan, 2014).

Table 1. U-Pb TIMS analytical data .

							Isotopic Ratios[6]								Ages[8] (Ma)						
Fraction[1]	Description[2]	Wt. µg	U ppm	Pb[3] ppm	$^{206}Pb/^{204}Pb$[4]	Pb[5] pg	$^{208}Pb/^{206}Pb$	$^{207}Pb/^{235}U$	±1SE Abs	$^{206}Pb/^{238}U$	±1SE Abs	Corr.[7] Coeff.	$^{207}Pb/^{206}Pb$	±1SE Abs	$^{206}Pb/^{238}U$	±2SE	$^{207}Pb/^{235}U$	±2SE	$^{207}Pb/^{206}Pb$	±2SE	% Disc
12AV-BT130 (Z11000)																					
B1 (11)	Br, El, Str, NM10	19	96	17	7404	3	0.01	1.96998	0.00228	0.18651	0.00017	0.928726048	0.07661	0.00004	1102.4	1.8	1105.3	1.6	1110.9	1.9	0.8
B2 (10)	Br, El, Str, NM10	21	92	16	5961	4	0.01	1.97198	0.0023	0.18672	0.00016	0.928578322	0.0766	0.00004	1103.6	1.8	1106.0	1.6	1110.7	1.9	0.7
B4 (5)	Br, El, Str, NM10	12	157	27	7197	3	0.01	1.96863	0.00237	0.18647	0.00018	0.924354866	0.07657	0.00004	1102.2	1.9	1104.8	1.6	1110.0	1.9	0.8
B5 (6)	Br, El, Str, NM10	14	203	35	9227	4	0.01	1.95946	0.00225	0.18562	0.00016	0.936024354	0.07656	0.00003	1097.6	1.8	1101.7	1.5	1109.8	1.8	1.2
Z1A (1)	Co, Clr, An, Frac, M10	11	224	48	10694.3	3	0.30	1.92427	0.00231	0.18245	0.00017	0.943328099	0.07649	0.00003	1080.3	1.9	1089.6	1.6	1108.0	1.8	2.7
Z1B (1)	Co, Clr, An, Frac, M10	14	544	115	18397.4	5	0.23	1.97189	0.00236	0.18702	0.00018	0.944364682	0.07647	0.00003	1105.2	1.9	1106.0	1.6	1107.4	1.7	0.2
Z1C (1)	Co, Clr, An, Frac, M10	15	210	47	14608.9	2	0.31	1.97760	0.00232	0.18743	0.00017	0.938764663	0.07652	0.00003	1107.4	1.9	1107.9	1.6	1108.8	1.8	0.1

Notes:

[1]Fraction name abbreviations: B=baddeleyite, Z=zircon; number of grains making up each fraction shown in parentheses; all zircon fractions were chemically abraded using a modified procedure from Mattinson (2005)

[2]Zircon/baddeleyite descriptions: An=anhedral, Clr=clear, Co=colourless, Br=brown, El=elongate, Frac=fractured, M10=magnetic@1.8A 10°SS, NM10=nonmagnetic@1.8A 10°SS, Str=striated

[3]Radiogenic Pb

[4]Measured ratio, corrected for spike and fractionation

[5]Total common Pb in analysis corrected for fractionation and spike

[6]Corrected for blank Pb and U and common Pb, errors quoted are 1 standard error (absolute); procedural blank values for this study are 0.1 pg U and 1 pg Pb; Pb blank isotopic composition is based on the analysis of procedural blanks; corrections for common Pb were made using Stacey and Kramers (1975) compositions

[7]Correlation coefficient

[8]Corrected for blank and common Pb; errors quoted are 2 standard error in Ma

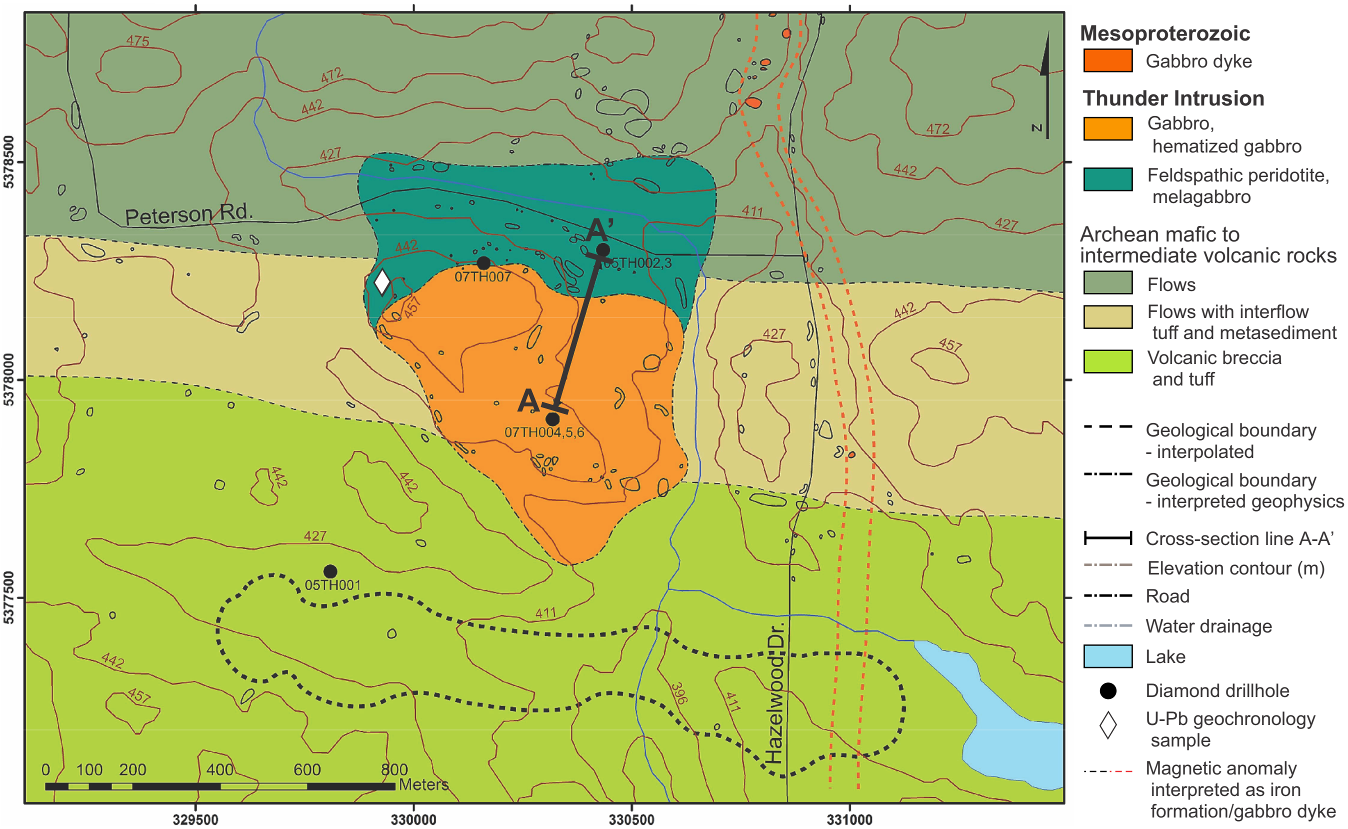

Figure 2. Geological map of the Thunder intrusion and vicinity at 1:9000 scale. Included on the map are the locations of the diamond drillholes, cross-section line, and geochronology samples. Geophysical interpretations are from OGS (2003).

Correlating petrographic observations, whole-rock geochemistry, and magnetic susceptibility defines a four-stage cumulate mineral paragenetic sequence: clinopyroxene + olivine, clinopyroxene + olivine + Fe-Ti oxide, plagioclase + clinopyroxene + Fe-Ti oxide, and plagioclase + clinopyroxene + Fe-Ti oxide + apatite (Trevisan, 2014).

Olivine analyses focused on a suite of samples collected from the lower mafic to ultramafic unit of DDH 07TH004 (n = 10). The coarser and least altered olivine crystals enclosed by plagioclase were preferred for analysis as they should have avoided potential exchange with adjacent sulphide minerals (Donoghue et al., 2014). No fresh olivine was found in the upper gabbroic unit. Both core and rim were analysed for multiple olivine grains from each sample. The full dataset is available in Trevisan (2014). Olivine forsterite compositions range from 56.3 to 86.9 mol% Fo, with an average of ~65 mol% Fo. There is little variation between core and rim measurements (typically <0.5 mol% Fo), indicating that cumulus olivine was not overly modified by sub-solidus re-equilibration with trapped silicate liquid (i.e. the trapped liquid shift; Barnes, 1986). Sample RTTC-BT-089 showed a wide range in mol% Fo values, from ~69 to 86, indicating disequilibrium along the basal contact of the lower mafic to ultramafic unit.

A sample of the lower mafic to ultramafic unit collected 20 cm from the wall-rock contact (sample RTTC-BT-089) was selected as being representative of a "quenched" parental liquid. With 10 modal% of olivine in sample RTTC-BT-089, it was assumed that the parental magma also contained 10 modal% of Fo_{86}

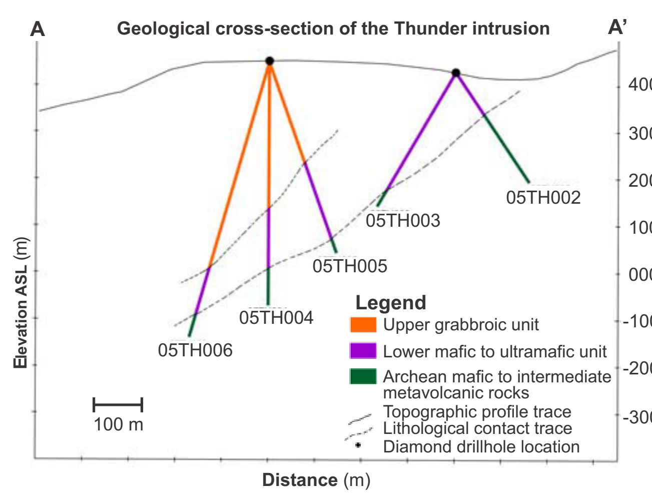

Figure 3. Geological cross-section of the Thunder intrusion looking towards 290°. For the location of the section line, see Figure 2.

olivine; both the Fo_{86} olivine and whole-rock composition were used in the mass balance equation of Roeder and Emslie (1970). The Mg# calculated using the estimate parent magma composition yielded ~57.

Radiogenic Sm-Nd and Rb-Sr Isotopes

Rb-Sr and Sm-Nd isotope analyses focused on ten samples from the upper gabbroic unit, lower mafic to ultramafic unit, and the metavolcanic wall rocks from DDH 07TH004. Values of $^{87}Sr/^{86}Sr_i$ ratios and εNd_t were calculated at time t = 1100 Ma and represent the 2σ uncertainty level. The upper gabbroic unit (n = 4) is characterized by $^{87}Sr/^{86}Sr_i$ ranging from 0.7031 to 0.7061, $^{143}Nd/^{144}Nd$ ranging from 0.511992 to 0.512127, and εNd_t ranging from -0.7 to 1.0. The lower mafic to ultramafic unit (n = 4) is characterized by 87Sr/86Sri ranging from 0.7288 to 0.7034, $^{143}Nd/^{144}Nd$ ranging from 0.512065 to 0.512298, and εNd_t ranging from 0.5 to 1.0. The metavolcanic wall rocks (n = 2) are characterized by $^{87}Sr/^{86}Sr_i$ ranging from 0.7071 to 0.7087, $^{143}Nd/^{144}Nd$ ranging from 0.511047 to 0.51186, and εNd_t ranging from -16.8 to -15.8.

Sulphur Isotopes and Se/S Ratios

Twenty samples from surface and DDH 07TH004 were analysed for $\delta^{34}S$ isotopes, including the upper gabbroic unit, the lower mafic to ultramafic unit, and the metavolcanic wall rocks. Values of $\delta^{34}S$ for the upper gabbroic unit (n = 10) range from -2.0 to 4.9‰; from -1.3 to 2.9‰ for the lower mafic to ultramafic unit (n = 6); and from -3.1 to 2.3‰ for the metavolcanic rocks (n = 10). In addition, three samples were analysed for $\delta^{33}S$ to investigate the involvement of crustal sulphur during mineralization. Values are presented in delta cap notation (where $\Delta^{33}S = \ln(\delta^{33}S+1)-0.515*\ln(\delta^{34}S+1)$; Ono et al., 2012): a surface and a drill-core sample of the lower mafic to ultramafic unit yielded values of 0.122 and 0.066‰, respectively, and a drill-core sample of the metavolcanic wall rock yielded a value of 0.149‰.

The samples used for the S-isotope analyses were also analysed for whole-rock Se concentrations. Ratios of $Se/S_{Tot} \times 10^6$ range from 400 to 2000 for the upper gabbroic unit (n = 5); from 180 to 3000 for the lower mafic to ultramafic unit (n = 6); and from 40 to 1000 for the metavolcanic rocks (n = 6). Anomalously high Se/S_{Tot} ratios were determined to be the result of some samples having S concentrations at or near the lower detection limit.

Sulphide and Platinum-Group Element Mineralogy

The basal mineralization zone, which is hosted by feldspathic peridotite of the lower mafic to ultramafic unit, is the primary mineralization in the Thunder intrusion and is interpreted to be the accumulation of immiscible sulphide droplets via gravitational settling. The upper gabbroic unit exhibits weak to no mineralization. Ni-Cu-PGE grades are highest in DDHs 07TH004, 005, and 05TH003, but are low in DDHs 07TH006 and 05TH002. Sulphides in the basal mineralization zone rarely comprise up to 30 modal% and are typically 1 to 5 modal%. Sulphide textures range from medium- to fine-grained disseminated, coarse-grained globular, and rarely net-textured. The primary sulphide mineralogy mainly consists of composite textured pyrrhotite and chalcopyrite (pyrrhotite > chalcopyrite) intergrown with minor Fe-Ti oxide. Rare inclusions of very fine-grained pentlandite, siegenite, sphalerite, cobaltite, cubanite. and galena are hosted by pyrrhotite and chalcopyrite. In addition, extensive secondary graphic and nickeliferous marcasite-pyrite-magnetite intergrowths occur replacing the primary sulphides.

Platinum-group minerals and precious-metal minerals that were identified by electron microprobe are summarized in Table 2 with the majority being Pd-rich telluride and bismuthide with minor Pt-rich arsenide.

Table 2. Summary of platinum-group minerals, precious-metal minerals identified in representative samples of the various styles of mineralization observed in the Thunder intrusion and footwall.

Intrusion-hosted		**Footwall-hosted**	
Mineral	Formula	Mineral	Formula
Upper zone		*Pyrrhotite-rich massive sulphide veinlet*	
Kotulskite	Pd(Te,Bi)	Naldrettite	Pd_2Sb
Basal zone		Stibiopalladinite	Pd_5Sb_2
Argentian pentlandite	$(Fe,Ni,Ag)_9S_8$	*Chalcopyrite-rich massive sulphide veinlets*	
Electrum	(Au,Ag)	Electrum	(Au,Ag)
Hessite	Ag_2Te	Native silver	Ag
Kotulskite	Pd(Te,Bi)		
Merenskyite	$(Pd,Pt)(Te,Bi)_2$		
Michenerite	(Pd,Pt)BiTe		
Sperrylite	$PtAs_2$		
unknown mineral	Pd_3Pt_3Sn		

Geochronology

Three single grain fractions of zircon and four multi-grain fractions of baddeleyite were analyzed and are shown in Figure 4. Two of the three zircon fractions are concordant, but all have consistent $^{207}Pb/^{206}Pb$ ages with a weighted mean of 1108.0 ± 1.0 Ma. All four baddeleyite fractions are slightly discordant, and three of them overlap within error. The weighted mean $^{207}Pb/^{206}Pb$ age of the baddeleyite fractions is 1110.3 ± 0.9 Ma. As observed in this study, others have noted a consistent discordance problem (and consequent shift to older $^{207}Pb/^{206}Pb$ ages) for baddeleyite relative to zircon (Paces and Miller, 1993 ; Heaman et al., 2007). The reason for this discordance is poorly understood

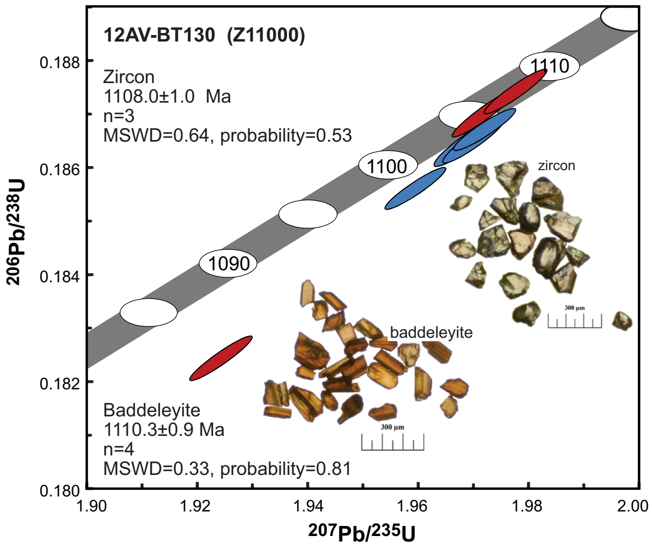

Figure 4. Concordia diagram illustrating geochronology results for zircon (red ellipses) and baddeleyite (blue ellipses) from the Thunder intrusion. The concordia curve is shown as a band incorporating uncertainties in the decay constant. Error ellipses and uncertainties in the weighted mean $^{207}Pb/^{206}Pb$ ages are given at 2σ. Inset photomicrographs illustrate a selection of grains that is representative of those analysed (300 μm scale bar).

but needs to be taken into account when comparing high-precision results of other samples. In order to permit the comparison of this age with earlier studies, the best estimate of the crystallization of the Thunder intrusion is the zircon weighted mean $^{207}Pb/^{206}Pb$ age of 1108.0 ± 1.0 Ma. Considering the recently proposed tectono-magmatic model of Miller and Nicholson (2013) the Thunder intrusion fits between the initial (1115–1110 Ma) to early (1110–1105 Ma) magmatic stages of the MCR evolution and falls within range of other fertile early-rift mafic to ultramafic intrusions, such as the Eagle at 1107.20 ± 5.7 Ma (Ding et al., 2010), Tamarack at 1105.6 ± 1.2 Ma (Goldner, 2011), and Seagull at 1112.80 ± 1.4 Ma (Heaman et al., 2007).

DISCUSSION

Petrology

The geochemical signature of the Thunder intrusion is broadly comparable to Sun and McDonough's (1989) modern plume-derived ocean island basalt (OIB). A negative Nb anomaly for the upper most section of the upper gabbroic unit, assimilation features (e.g. irregular quartz-rich fragments surrounded by pods of granophyre), and an up-hole increase in Th concentrations are all consistent with contamination by older crustal material. The radiogenic Sm-Nd and Rb-Sr isotope signature is similar to the contamination trends of the Nipigon sills, which are interpreted to be the result of contamination by shallow basin-filling sedimentary rocks (Fig. 5; Hollings et al., 2007b; Trevisan, 2014).

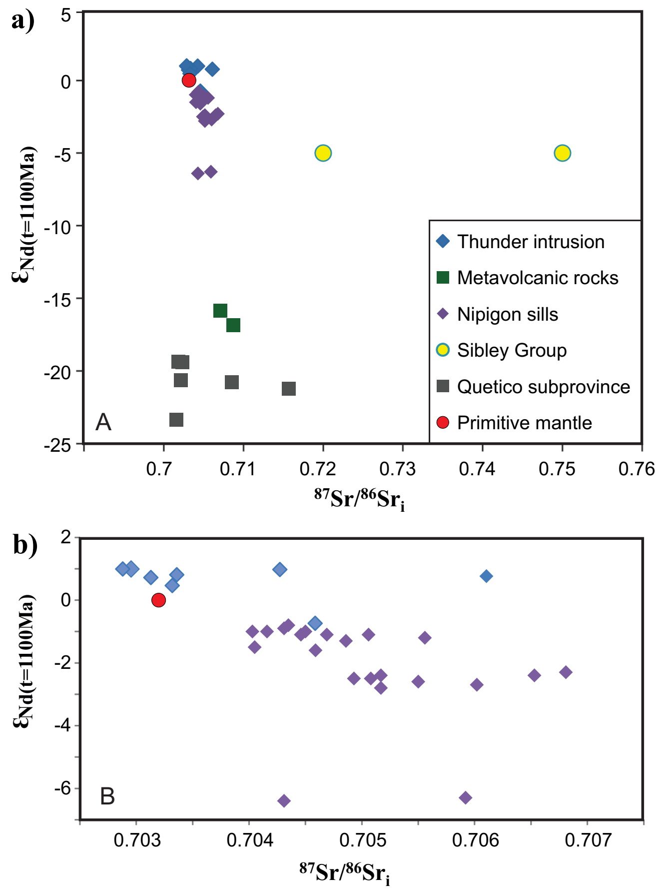

Figure 5. Plots of εNd_t versus $^{87}Sr/^{86}Sr_i$ at 1100 Ma for the host rocks and units of the **(a)** Thunder intrusion (diamond drillhole 07TH004), the Nipigon sills, Quetico subprovince metasedimentary rocks, and Sibley Group sedimentary rocks; and **(b)** Close-up of the Thunder intrusion and Nipigon sill dataset relative to primitive mantle. Data sources include primitive mantle values from Nicholson and Shirey (1990), Nipigon sill data from Hollings et al. (2007b), Quetico subprovince data from Pan et al. (1999), and Sibley Group data from Metasaranta et al. (pers. comm., 2005).

The lack of correlation between Sr_i and in εNd_t (r = -0.28) implies that the metavolcanic rocks that immediately underlie the Thunder intrusion were not a likely contaminant to the magma. Expansion of the radiogenic isotope study is required to investigate other possible contaminants.

On a plot of Gd/Yb_n versus La/Sm_n, both intrusive units of the Thunder intrusion plot slightly above the field of the mafic to ultramafic intrusions and sills of the Nipigon Embayment (e.g. Hele intrusion and Shillabeer sill, respectively; Fig. 6). The high Gd/Yb_n values are consistent with the interpretation of Hollings et al. (2007a) that the parent magmas of the mafic to ultramafic intrusions of the Nipigon Embayment were derived from a deeper source than the diabase sills (e.g. Nipigon sills). Regardless of Archean host rock, the Thunder intrusion's geochemical signature is consistent with other known early-rift mafic to ultramafic intrusions, including relatively high Gd/Yb_n values that

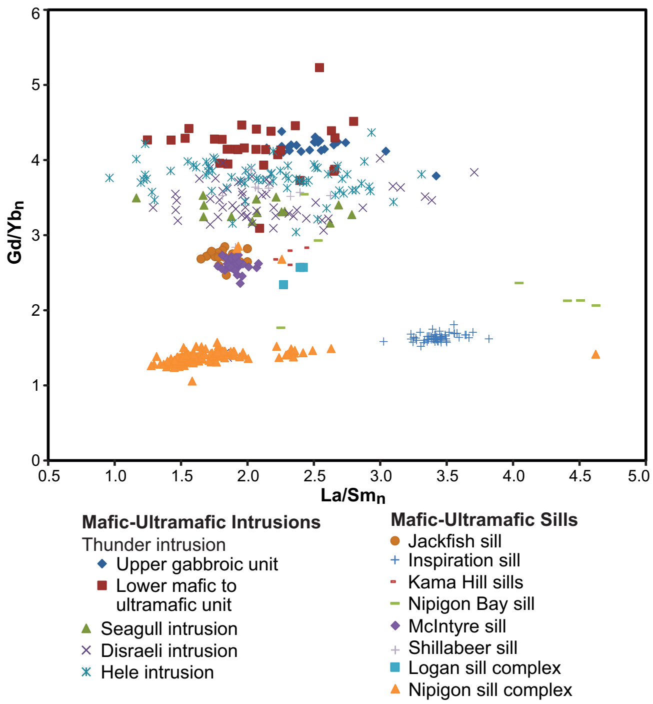

Figure 6. Plot of Gd/Yb$_n$ versus La/Sm$_n$ for the upper gabbroic unit and lower mafic to ultramafic unit of the Thunder intrusion and other intrusions of the Nipigon Embayment. Chondrite-normalized rare earth element ratios calculated from the values of Sun and McDonough (1989). Nipigon Embayment data from Cundari et al. (2013).

are similar to mafic to ultramafic intrusions in the Nipigon Embayment (Hollings, 2007a), and has OIB-like characteristics that suggest crustal contamination (e.g. Heggie, 2005; Hollings et al., 2007b).

The Wawa and Quetico subprovince boundary is roughly outlined by granitoid bodies of the Dog Lake Granite Chain and Nipigon Bay granite. These granitoid bodies are interpreted to have been emplaced along crustal-scale faults that formed the terrane boundaries as “stitching plutons” (e.g. Hollings and Kuzmich, 2014). The spatial proximity of early-rift mafic to ultramafic intrusions, such as Thunder, Sunday Lake, and Current Lake, and the Dog Lake Granite Chain suggests a possible structural control on the distribution of mafic to ultramafic intrusions containing Ni-Cu-PGE sulphide mineralization in the northern Lake Superior region north of the Canada-United States border. The Thunder parent magma likely travelled along the deep-seated structure represented by the Wawa and Quetico subprovince boundary, which was reactivated during the Mesoproterozoic rifting event (Trevisan, 2014). The structural control on the primary distribution of mafic to ultramafic intrusions containing Ni-Cu-PGE sulphide mineralization in the roots of large igneous provinces has been observed elsewhere, such as in the Huangshandong, Huanshang, and Jinchuan intrusions in China (Lightfoot and Evans-Lamswood, 2014). The low Mg# (~57) estimate for the parent magma likely represents a more evolved magma than the other early-rift mafic to ultramafic intrusions in the MCR. The involvement of multiple staging chambers during the ascent of the Thunder intrusion may account for the evolved composition, possibly reflecting a conduit system similar to the one proposed for the Noril’sk-Talnakh deposits (Arndt, 2005).

Mineralization

As this intrusion is hosted by metavolcanic rocks bearing Ag and Au mineralization (MacDonald, 1939; Thomson, 1989), it is possible that wall-rock assimilation could account for the precious metal mineralogy observed in the basal mineralization zone. Whole-rock geochemistry indicates fractionated Ni-Cu-PGE patterns with depletion in iridium-subgroup PGEs relative to platinum-subgroup PGEs for the disseminated sulphide mineralization hosted by the Thunder intrusion’s lower mafic to ultramafic unit. The Thunder intrusion’s Ni-Cu-PGE patterns are similar to the upper massive sulphide zone, semi-massive sulphide zone, and chalcopyrite-rich veins of the Eagle deposit (Ding et al., 2011). This similarity is consistent with an early sulphide liquid-phase forming deeper in the system, which has concentrated the iridium-subgroup PGEs. The sulphur source appears to be of mantle origin, however, the assimilation of crustal sulphur is a possibility that is hard to resolve as the wall-rock S isotope and S/Se$_{Tot}$ signature is similar to that of upper mantle.

IMPLICATIONS FOR EXPLORATION

This study has improved the emplacement model for the Thunder intrusion and has provided key insights into early-rift mafic to ultramafic magmatism, revealing a single, differentiated, Cu-(Ni)-PGE mineralization magmatic body that has undergone fractionation and cumulate processes. Regardless of host rock, the Thunder intrusion’s geochemical signature is consistent with the other known early-rift mafic to ultramafic intrusions, including relatively high Gd/Yb$_n$ values that are similar to mafic to ultramafic intrusions in the Nipigon Embayment (Hollings, 2007a), and has OIB-like characteristics with indications of crustal contamination (e.g. Heggie, 2005; Hollings et al., 2007b). Based on whole-rock geochemistry and olivine chemistry (e.g. Ding et al., 2010; Foley, 2011; Goldner, 2011), the parental magma that formed the Thunder intrusion is relatively more evolved than other mineralized early-rift mafic to ultramafic intrusions, such as BIC, Tamarack, and Eagle. Our research on the Thunder Cu-(Ni)-PGE-bearing intrusion, reflects the possible involvement of multiple staging chambers during the ascent of a more primitive parent magma.

The Thunder parent magma likely travelled along a conduit through reactivated deep-seated structures during the Mesoproterozoic rifting event (Trevisan, 2014). The relative proximity of the Dog Lake Granite Chain and early-rift mafic to ultramafic intrusions, such as Thunder, Sunday Lake, and Current Lake, indicates a possible structural conduit along the Wawa and Quetico subprovince boundary.

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