GS2023-9

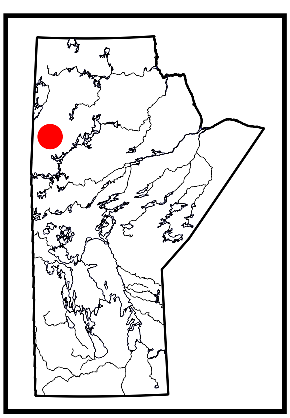
Field relationships, geochemical characteristics and metallogenic implications of gabbroic intrusions in the Paleoproterozoic Lynn Lake greenstone belt, northwestern Manitoba (parts of NTS 64C10–12, 14–16)

by X.M. Yang

In Brief:

- A number of gabbroic intrusions is evaluated for Ni-Cu fertility based on field relationships, geodynamic settings and geochemical characteristics
- Sulphide saturation in mafic magmas is largely caused by crustal contamination
- Low concentrations in platinum-group elements reflect fractionation of the mafic magma(s) formed by low-degree partial melting of the mantle

Citation:
Yang, X.M. 2023: Field relationships, geochemical characteristics and metallogenic implications of gabbroic intrusions in the Paleoproterozoic Lynn Lake greenstone belt, northwestern Manitoba (parts of NTS 64C10–12, 14–16); *in* Report of Activities 2023, Manitoba Economic Development, Investment, Trade and Natural Resources, Manitoba Geological Survey, p. 73–89.



Summary

In 2023, the Manitoba Geological Survey carried out a schematic study of gabbroic intrusions in the Paleoproterozoic Lynn Lake greenstone belt to address two essential questions: 1) why are some intrusions host to magmatic nickel-copper mineralization, whereas others are barren; and 2) what are the key controls on the mineralization. As a first step to tackling these questions, geochemical data on gabbroic rocks and related deposits published by the Manitoba Geological Survey were reviewed to extract valuable information on the metallogeny of the magmatic nickel-copper deposits in the belt. Several gabbro intrusions were then selected for further examination to investigate their relationships to the country rocks; their internal variation in mineralogy and grain size; their structural and magnetic susceptibility; and the presence and/or absence of sulphide minerals. Representative samples were also collected for further lithogeochemical, neodymium isotope and uranium-lead zircon geochronological studies.

Fertile gabbroic intrusions seem to occur mostly in the northern belt, whereas barren intrusions are present in the southern belt of the Lynn Lake greenstone belt. Geochemically, both the fertile and barren intrusions are dominantly metaluminous and tholeiitic (or calcic) to calcalkaline, showing typical volcanic-arc signatures. The geometry of the gabbro intrusions, ranging from vertical and tube-shaped (e.g., the Lynn Lake A and EL plugs) to tabular (Fraser Lake), appears to reflect the differences in the geological settings of magma emplacement and in the dynamics of mafic magmas. Geochemical proxies, such as highly siderophile elements including platinum-group elements, sulphur and oxygen stable isotopes, are therefore used to help assess the major controls on nickel-copper mineralization with respect to local geological settings, degree of fractionation and source heterogeneity or disparate degrees of partial melting of the mantle source. Relatively low-degree partial melting of the mantle source, early sulphide segregation of fractionating mafic magmas emplaced in an intra-oceanic–arc extensional setting and crustal contamination (particularly by volcanogenic massive-sulphide deposits) triggering sulphide saturation in the magmas are thought to be the key controls on nickel-copper mineralization in the Lynn Lake greenstone belt.

Introduction

Major to giant nickel–copper–platinum-group element (Ni-Cu-PGE) ore deposits are genetically associated with mafic-ultramafic mineral (magmatic) systems derived from the mantle and emplaced into extensional settings at continental margins (e.g., Lightfoot et al., 1990; Naldrett, 2004; Barnes and Lightfoot, 2005; Houlé et al., 2008; Begg et al., 2010; Lightfoot, 2017; Barnes et al., 2020). However, the nature of magmatic Ni-Cu-PGE deposits with relatively small tonnage and high grade in orogenic belts is less well understood. Although these deposits are enigmatic in origin, they have recently become more important and attractive exploration targets because of the high demand for critical metals and a foreseeable supply shortage (e.g., Maxeiner and Rayner, 2017; Yildirim et al., 2020; Deng et al., 2022; U.S. Geological Survey, 2023). The Lynn Lake magmatic Ni-Cu deposit (Pinsent, 1980) is hosted in the Lynn Lake intrusion. It occurs together with other mafic-ultramafic intrusions intruding the Wasekwan group supracrustal rocks of the Lynn Lake greenstone belt (Figure GS2023-9-1; Gilbert et al., 1980; Syme, 1985; Gilbert, 1993; Zwanzig et al., 1999; Yang and Beaumont-Smith, 2015; Hastie et al., 2018; Lawley et al., 2020, 2023; Yang, 2022). This provides an excellent opportunity to investigate the metallogeny of magmatic Ni-Cu mineral deposits in orogenic belts.

In 2023, the Manitoba Geological Survey (MGS) continued its multiyear bedrock geological mapping project in the Paleoproterozoic Lynn Lake greenstone belt (LLGB) in northwestern Manitoba (Figure GS2023-9-1), focusing on a schematic study of gabbroic intrusions in the belt. The objective of this

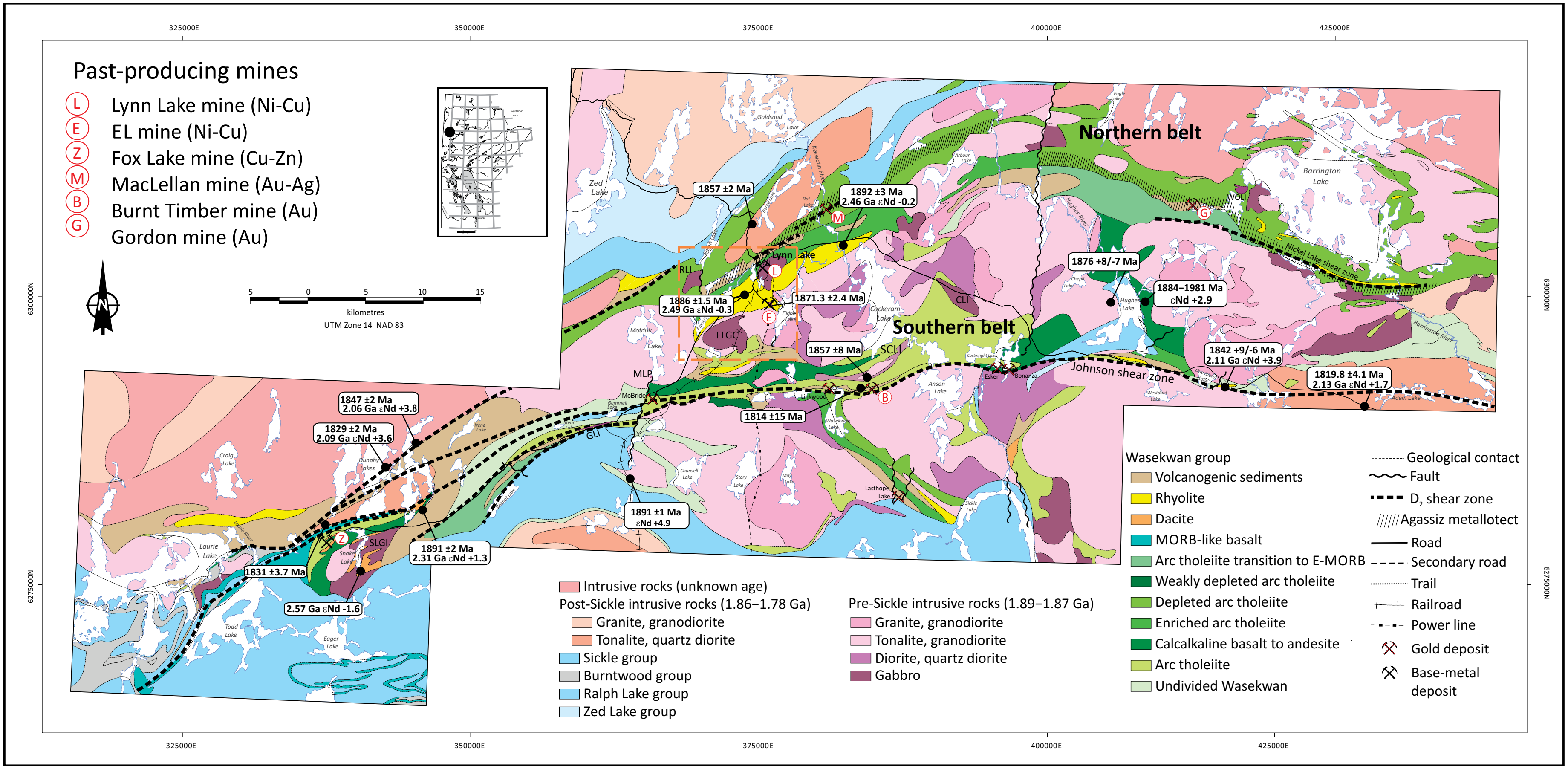


Figure GS2023-9-1: *Regional geology with uranium-lead zircon ages and neodymium isotopic compositions of the Lynn Lake greenstone belt (modified and compiled from Gilbert et al., 1980; Manitoba Energy and Mines, 1986; Gilbert, 1993; Zwanzig et al., 1999; Turek et al., 2000; Beaumont-Smith and Böhm, 2002, 2003, 2004; Beaumont-Smith et al., 2006; Jones et al., 2006; Beaumont-Smith, 2008; Yang and Beaumont-Smith, 2015, 2016, 2017; Lawley et al., 2020; Yang, 2022). Localities of gabbroic intrusions sampled in this study are shown. The location of Figure GS2023-9-2 is indicated by the orange box. Abbreviations: CLI, Cartwright Lake intrusion; FLGC, Fraser Lake gabbro complex; GLI, Gemmell Lake intrusion; MLP, Motriuk Lake plug; MORB, mid-ocean–ridge basalt; RLI, Ralph Lake intrusion; SCLI, Southern Cockeram Lake intrusion; SLGI, Snake Lake gabbro intrusion; WOLI, White Owl Lake intrusion.*

study was to evaluate the critical controls on magmatic Ni-Cu-PGE mineralization via a review of the MGS published data followed by field observations and investigations; structural and magnetic susceptibility (MS) measurements of outcrops; and geochemical sampling of representative bulk-rock samples. Results from this study indicate that metaluminous, tholeiitic to calcalkaline mantle-derived mafic magmas may have been largely contaminated by crustal materials, which may have triggered their sulphide saturation and segregation in the magmas as well as Ni-Cu mineralization, mostly at the base of the mafic-ultramafic intrusions. Structural analysis of the deformed gabbroic intrusions can help target Ni-Cu mineralization through reconstruction of their original configuration.

During the course of fieldwork this summer, forty-two whole-rock samples (including five gabbro samples from Corazon Mining Limited drillcore) were collected for geochemical analysis, including five for Sm-Nd isotopes and two for U-Pb zircon age determination. The geochronology work is to be carried out in collaboration with the Geological Survey of Canada through phase 6 of its Targeted Geoscience Initiative program (TGI-6). The results of the lab analyses are pending and will be reported in subsequent MGS publications.

Regional geology

The LLGB, an important element of the Paleoproterozoic Trans-Hudson orogen (Hoffman, 1988; Lewry and Collerson, 1990; Ansdell, 2005; Corrigan et al., 2007, 2009; Corrigan, 2012), is endowed with several styles of mineralization, such as volcanogenic massive sulphide (VMS) zinc-copper (Zn-Cu), magmatic nickel-copper-cobalt (Ni-Cu-Co) and orogenic gold (Au; Figure GS2023-9-1). This belt is bounded to the north by the Southern Indian domain and flanked to the south by the Kisseynew domain (Gilbert et al., 1980; Zwanzig and Bailes, 2010; Martins et al., 2022). It is composed of two east- to northeast-trending, steeply dipping belts (Figure GS2023-9-1) consisting of various supracrustal rocks of the Wasekwan group that were intruded by granitoid plutons of the 1.89–1.87 Ga Pool Lake intrusive suite (Baldwin et al., 1987). Younger, molasse-type sedimentary rocks of the Sickle group (≥1.836 Ga; see Lawley et al., 2020) unconformably overlie the Wasekwan group and the Pool Lake intrusive suite. Based on their crosscutting relationships with the Sickle group, the granitoid intrusions in the LLGB are divided into pre- and post-Sickle intrusions. The supracrustal rocks and the granitoid rocks experienced peak amphibolite-facies metamorphism at ca. 1.81–1.80 Ga (Lawley et al., 2020, 2023). Gabbros in the LLGB were metamorphosed to amphibolites or metagabbros in terms of their mineral assemblage; however, this report omits the prefix 'meta' in the rock names for brevity.

Significant differences in the geology and geochemistry of the northern and southern belts of the LLGB may reflect regional differences in tectonic settings obscured by structural transposition of multiple deformation events (D_1 to D_6; Zwanzig, 2000; Beaumont-Smith and Böhm, 2002, 2003, 2004; Jones et al., 2006). The northern and southern belts contain disparate volcanic assemblages that were later structurally juxtaposed, likely representing a tectonic collage (Zwanzig et al., 1999) formed by northward subduction, followed by contraction and underthrusting of the Kisseynew domain beneath the LLGB during terminal collision (White et al., 2000). Field observations and historical drilling records indicate the presence of disseminated to massive sulphides (e.g., sphalerite, chalcopyrite, pyrrhotite) in the Wasekwan supracrustal rocks, including the Fox VMS Zn-Cu ore deposit (Gilbert et al., 1980; Fedikow and Gale, 1982; Baldwin, 1989; Ferreira, 1993; Yang and Beaumont-Smith, 2015; Yang, 2022).

Geological settings

Recent bedrock geological mapping demonstrates that various gabbroic intrusions occur in both the northern and southern belts of the LLGB, including the Lynn Lake (A plug, EL plug), Fraser Lake, Ralph Lake, Cartwright Lake, Motriuk Lake, White Owl Lake, Gemmell Lake, Southern Cockeram Lake and Snake Lake areas (Figure GS2023-9-1). It should be noted that the Motriuk Lake plug comprises very coarse grained pyroxenite (Yang, 2019), which displays cumulative texture and contains abnormally high Cr values (1540 ppm; see Yang, 2023, Table 1_2), and that the Cartwright Lake intrusion has the highest MS values (80×10^{-3} to 150×10^{-3} SI; this study) registered in the gabbroic rocks of the LLGB, although no notable Ni-Cu mineralization is evident in its exposures. These gabbroic intrusions are all ascribed to the pre-Sickle intrusive suite and detailed descriptions of the gabbroic rocks can be found in the MGS publications by Yang and Beaumont-Smith (2015, 2016, 2017), Yang and Lawley (2018), and Yang (2019, 2021, 2022). Bulk-rock geochemical data of representative samples for these intrusions are tabulated in DRI2023013[1] (Yang, 2023); acquisition of these data began in 2015, when the current mapping project started.

The Lynn Lake and Fraser Lake gabbroic intrusions are the focus of the following sections as they host magmatic Ni-Cu ore deposits. The other intrusions are barren, although some of their outcrops show evidence of trace sulphide dissemination.

Lynn Lake gabbroic intrusion

The Lynn Lake gabbroic intrusion (Childs, 1950; Gilbert et al., 1980; Yang and Beaumont-Smith, 2015) comprises two separate plugs; A plug (~4 km^2) and EL plug (~0.12 km^2; Figure GS2023-9-2). The A plug contains approximately 28.4 Mt of ore grading 0.91% Ni and 0.49% Cu, with an average Ni/Cu ratio of 1.86,

[1] MGS Data Repository Item DRI2023013, containing the data or other information sources used to compile this report, is available online to download free of charge at https://manitoba.ca/iem/info/library/downloads/index.html, or on request from minesinfo@gov.mb.ca, or by contacting the Resource Centre, Manitoba Economic Development, Investment, Trade and Natural Resources, 360-1395 Ellice Avenue, Winnipeg, Manitoba R3G 3P2, Canada.

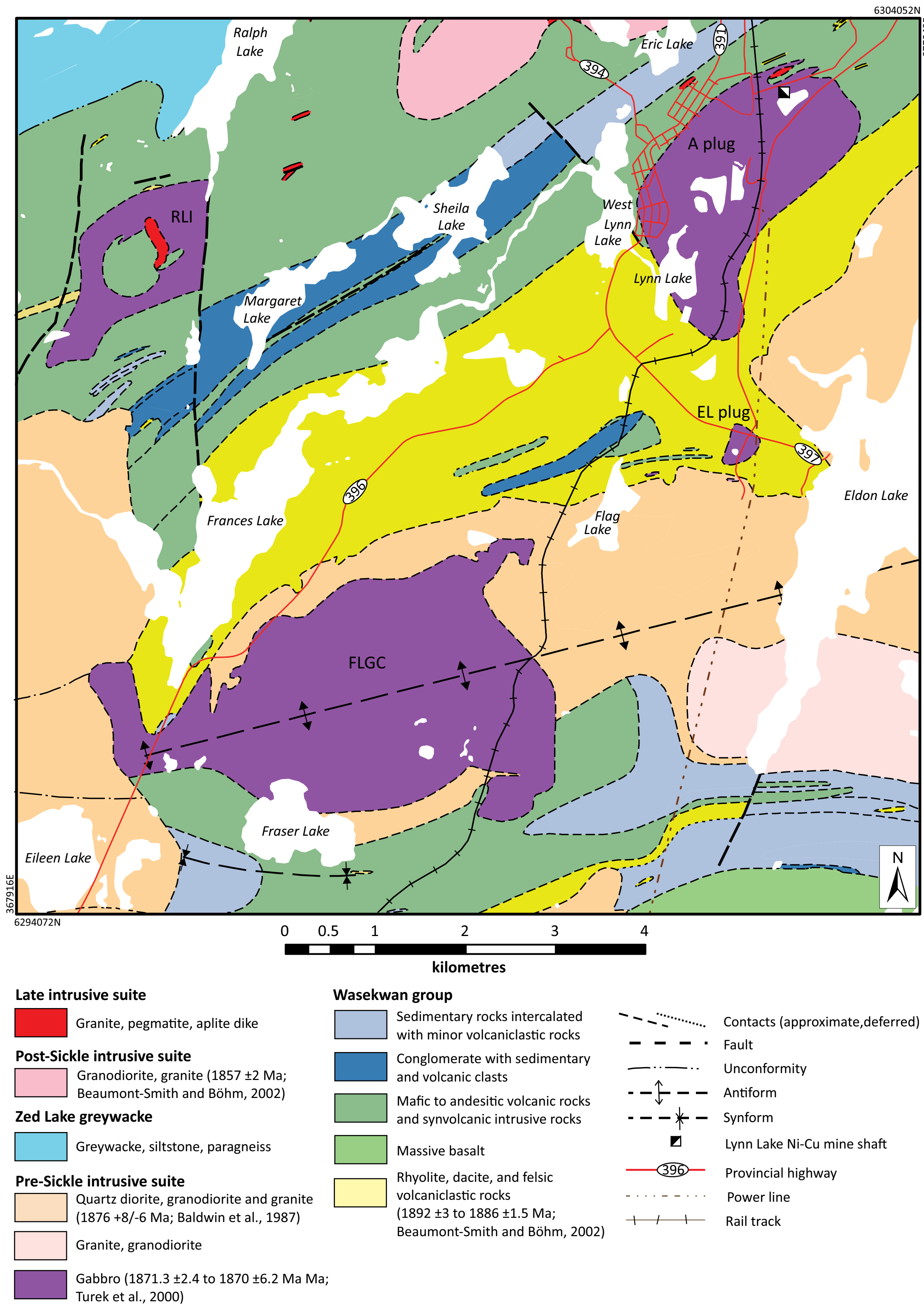


Figure GS2023-9-2: *Geology of gabbroic intrusions in the Lynn Lake area (modified from Gilbert et al., 1980; Yang and Beaumont-Smith, 2015; Manitoba Agriculture and Resource Development, 2021; Yang, 2021), showing geological relationships between the Lynn Lake A plug and EL plug, and the Fraser Lake gabbro complex associated with magmatic nickel-copper mineralization. Abbreviations: FLGC, Fraser Lake gabbro complex; RLI, Ralph Lake intrusion.*

and the EL plug has 1.9 Mt of ore grading 2.07% Ni and 0.76% Cu, with a Ni/Cu ratio of 2.72 (Pinsent, 1980). Some 16.3 Mt of ore grading 0.77% Ni and 0.33% Cu was produced from 1953 to 1976; a significant amount of Ni-Cu ore remains unmined below ground (https://corazon.com.au), where high concentrations of Co are also to be found (see below).

A plug

The A plug is emplaced into the Wasekwan group volcanic to volcaniclastic rocks and appears to be a vertical intrusion, with fabrics generally parallel to the regional structural trend (Pinsent, 1980; Dunsmore, 1986; Yang and Beaumont-Smith, 2015). Inclusions of the country rocks are variable in composition, size and shape; some of the xenoliths display diffusive edges, indicative of assimilation by intruding mafic magmas (Figure GS2023-9-3a). Contact-metamorphism aureoles are not well developed, likely due to a relatively smaller difference in temperature between the supracrustal succession and the intrusion. The A plug is composed primarily of medium-grained gabbro (and/or amphibolite) associated with minor peridotite, norite, mottled gabbro and diorite to quartz diorite. Magmatic fractionation led to the formation of very coarse grained to pegmatitic leucogabbro to anorthositic gabbro as in situ patches and/or pods in the intrusion (Figure GS2023-9-3b). More ultramafic phases are noted to occur mostly in the western section of the A plug, where they are associated with most of the Ni-Cu sulphide mineralization (Pinsent, 1980; Dunsmore, 1986).

Late diabase dikes of about 10 to 50 cm in width, trending north-northeast and west-northwest, cut the A plug gabbro intrusion in places. The diabase dikes have higher MS values (1.38×10^{-3} to 1.808×10^{-3} SI) than the A plug gabbros (0.23×10^{-3} to 0.954×10^{-3} SI). This confirms that both the magnetic high and low domains are present in the A plug, as demonstrated by detailed magnetic survey data collected by Corazon Mining Limited (https://corazon.com.au).

EL plug

The EL plug, dated at 1871.3 ±2.4 Ma (Turek et al., 2000), was emplaced into the ca. 1892–1886 Ma Lynn Lake rhyolite of the Waskewan group (Gilbert et al., 1980; Pinsent, 1980; Dunsmore, 1986; Beaumont-Smith and Böhm, 2002). There is no sign of a chilled margin on the contact of the EL plug with the Wasekwan rhyolitic volcanic to volcaniclastic rocks, although xenoliths of felsic to mafic volcanic rocks are evident. This plug shows a cored pipe structure narrowing from a surface diameter of about 500 m to a diameter of 200 m at depth (Pinsent, 1980).

The EL plug consists dominantly of medium-grained gabbro with minor diorite and peridotite, with an outer margin of contact-diorite and gabbro, and an inner core of gabbro (and/or amphibolite) and peridotite (Pinsent, 1980; Dunsmore, 1986). Locally, primary layering is well preserved, manifested by alternating plagioclase- and amphibole-rich layering (Figure GS2023-9-3c). As with the A plug, late mafic, west-northwest-trending (diabase) dikes cut the EL plug (Figure GS2023-9-3d); these are likely postmineralization dikes (Pinsent, 1980). Notably, there is no remarkable difference in the MS values between the dikes (0.613×10^{-3} to 0.725×10^{-3} SI) and EL gabbros (0.418×10^{-3} to 0.704×10^{-3} SI).

High-grade mineralization consists mainly of sulphide breccia-type ore in the core of the EL plug from the surface to about 300 m in depth; however, low-grade disseminated ore extends from the surface to about 925 m in depth (Pinsent, 1980). Primary sulphide minerals are pyrrhotite, pentlandite and chalcopyrite, with lesser to trace amounts of pyrite and sphalerite.

Fraser Lake gabbro complex

The Fraser Lake gabbro complex (FLGC; Hulbert, 1978), dated at 1870 ±6.2 Ma (Turek et al., 2000), is a tabular intrusion about 9.2 km^2 in area (Childs, 1950; Gilbert et al., 1980). The FLGC intrudes the Wasekwan group supracrustal rocks and has been cut by large granitoid plutons (Figure GS2023-9-2). Field observations revealed the presence of diverse volcaniclastic to basaltic xenoliths in the FLGC (Figure GS2023-9-3e), which is cut by granite dikes (Figure GS2023-9-3f). At contact zones, both volcanic and gabbroic inclusions are evident in the granitoid plutons southeast of Frances Lake and southwest of Flag Lake.

The FLGC is composed mostly of medium-grained gabbro with minor peridotite and amphibole (pseudomorphs of pyroxene)-phyric fine-grained gabbro. The gabbro appears homogeneous in mineralogy (~55 to 70% amphibole and ~30 to 45% plagioclase) and texture in most outcrops. It is metamorphosed to amphibolite facies, resulting in amphibole replacing primary pyroxene despite preservation of the magmatic texture. Green fibrous amphibole (actinolite-tremolite) occurs mostly along foliation planes and is likely attributed to retrograde metamorphism at greenschist-facies conditions. Minor amounts of finely disseminated sulphide minerals (e.g., pyrrhotite, chalcopyrite) and magnetite occur in gabbroic outcrops, but no major accumulation of sulphide is evident in most exposures (e.g., Childs, 1950; Hulbert, 1978; Dunsmore, 1986; this study). In 2023, Corazon Mining Limited reported an intersection of 55.4 m of sulphide (pyrrhotite-pentlandite-chalcopyrite) mineralization, including metre-scale intervals of massive sulphide intermixed with semimassive to disseminated sulphides, within the FLGC.

Magnetic susceptibility values of the FLGC gabbros range from 0.547×10^{-3} to 8.22×10^{-3} SI despite the presence of magnetic low and high domains within the intrusion, which are higher than most of the surrounding granitoid rocks (mostly $<0.5 \times 10^{-3}$ SI), as shown in an aeromagnetic survey image from Corazon Mining Limited (https://corazon.com.au).

Geochemical characteristics

Geochemical data including sulphur (S) and oxygen (O) stable isotope data of mafic-ultramafic rocks in the LLGB (Zwanzig et

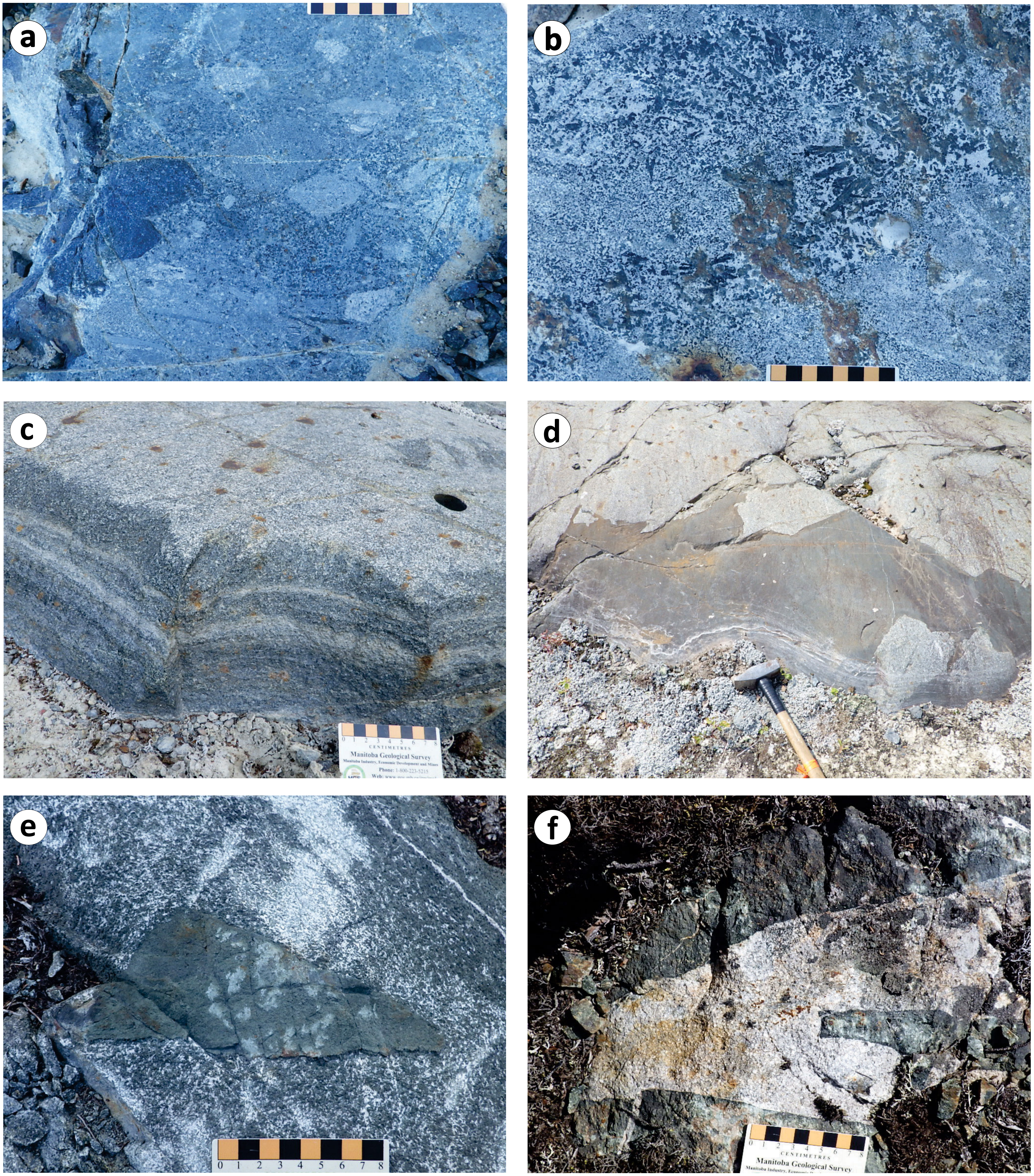


Figure GS2023-9-3: *Field photographs of gabbroic rocks in the Lynn Lake area, showing* ***a****) subrounded to angular xenoliths of basaltic to felsic and sedimentary rocks trapped in the A plug (375972E, 6302850N), with some xenoliths showing diffusive edges that is evidence for assimilation by intruding mafic magmas;* ***b****) very coarse grained to pegmatitic leucogabbro to anorthositic gabbro pod and/or patch in the A plug (375959E, 6302859N);* ***c****) primary layering in the EL plug (375836E, 6299203N);* ***d****) fine-grained mafic (diabase) dike cutting the EL plug gabbro (375836E, 6299203N);* ***e****) angular aphanitic basalt xenolith in the Fraser Lake gabbro complex (372429E, 6297114N);* ***f****) medium-grained granite dike cutting the Fraser Lake gabbro complex (372461E, 6297269N). All co-ordinates are in UTM Zone 14, NAD83.*

al., 1999; Hulbert and Scoates, 2000; Peck et al., 2000; Beaumont Smith, 2008), together with recently acquired data presented in DRI2023013 (Yang, 2023), are reviewed to extract some critical information about the metallogeny of the gabbroic intrusions. As the datasets contain different suites of elements analyzed using diverse techniques[2], these data are plotted separately in a set of diagrams in the following subsections to illustrate discernable features that can be used for fingerprinting magmatic sources and processes as well as recognizing Ni-Cu mineralization in the mafic-ultramafic mineral systems.

Geochemically, the gabbroic samples from both the fertile and barren intrusions are dominantly metaluminous and tholeiitic (or calcic) to calcalkaline based on the Shand index (Maniar and Piccoli, 1989) as well as the Rittmann Serial Index (σ) and Nb/Y ratios (Yang, 2007; X.M. Yang and C.J.M. Lawley, work in progress). These samples also show typical volcanic-arc signatures, as manifested by enrichment in large-ion lithophile elements relative to high-field-strength elements (Yang and Lawley, 2018; Yang, 2023). They are coeval with the Farley Lake A-type granites that were interpreted to have been emplaced in an intra-oceanic–arc setting (X.M. Yang and C.J.M. Lawley, work in progress), although part of the Wasekwan volcanic rocks is suggested to have formed at a rifted continental margin (e.g., Glendenning et al., 2015).

The niobium/thorium (Nb/Th) ratios of mafic-ultramafic rocks are sensitive to crustal contamination and copper/zirconium (Cu/Zr) ratios are sensitive to the state of sulphur saturation in the mafic melts (Lightfoot et al., 1990). Figure GS2023-9-4

[2] For details concerning detection limits, precision and accuracy of the analyses, please refer to Zwanzig et al. (1999), Hulbert and Scoates (2000), Peck et al. (2000), Beaumont Smith (2008) and Yang (2023).

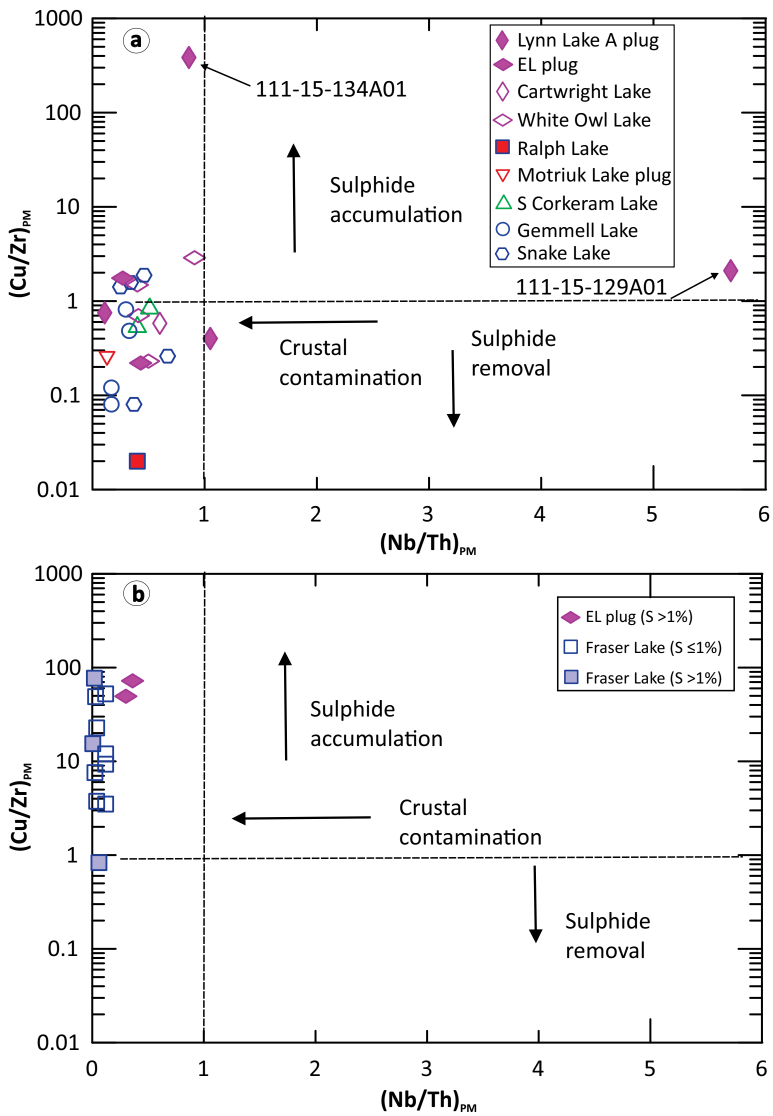


***Figure GS2023-9-4**: Plots of $(Cu/Zr)_{PM}$ versus $(Nb/Th)_{PM}$ in: **a)** unmineralized gabbroic rocks; and **b)** sulphide-bearing gabbros in the Lynn Lake greenstone belt. Data plotted in (a) from Yang (2023) and in (b) from Hulbert and Scoates (2000). Primitive mantle-normalized ($_{PM}$) values from McDonough and Sun (1995).*

shows variation in the primitive mantle-normalized $(Cu/Zr)_{PM}$ and $(Nb/Th)_{PM}$ ratios of selected gabbroic intrusions, which suggests that crustal contamination plays an important role in triggering sulphide saturation in mafic melts, regardless if it is mineralized or barren (Figure GS2023-9-4a, b). Sample 111-15-129A01 has an unusually high $(Nb/Th)_{PM}$ of 5.7, most likely reflecting the accumulation of Nb-bearing phases such as ilmenite or magnetite (Figure GS2023-9-4a). A mineralized gabbro (sample 111-15-134A01) has a $(Cu/Zr)_{PM}$ ratio >437 and a $(Nb/Th)_{PM}$ ratio of 0.75 (Yang, 2023) as Cu content is higher than 10 000 ppm (Yang, 2023, Table 2), and is plotted on the diagram using the analytical maximum value to illustrate the remarkable effect of sulphide accumulation (Figure GS2023-9-4a). Furthermore, the presence of high Zn contents in the Lynn Lake Ni-Cu deposits (Hulbert and Scoates, 2000; Peck et al., 2000) suggests that VMS deposits associated with the Wasekwan volcanic and sedimentary succession assimilated by intruding mafic-ultramafic magmas may have played an important role in providing external sulphur required for their sulphide saturation, segregation and mineralization (e.g., Lightfoot et al., 1990; Barnes and Lightfoot, 2005).

The Lynn Lake intrusion and the FLGC samples (n = 78; Hulbert and Scoates, 2000) display high sulphur/selenium (S/Se) ratios (the plot of S/Se versus aluminium oxide [Al_2O_3] is not shown), mostly higher than the mantle value (3000 ±200; see Lorand et al., 2021). This further confirms the effect of crustal contamination on these intrusions.

Metal tenors (i.e., metal contents in 100% sulphide) are calculated for 262 samples in the dataset of Peck et al. (2000), with the assumption that the metals are hosted in pyrrhotite, pentlandite and chalcopyrite (Barnes and Lightfoot, 2005). The calculated metal tenors display positive correlation between platinum, palladium and gold (Pt+Pd+Au) in ppb versus (Pt+Pd) in ppm/(Cu+Ni) in wt. % ratios, with a correlation coefficient (r) of 0.58 (n = 262). They show that barren gabbro intrusions (e.g., Cartwright Lake) appear to have higher (Pt+Pd)/(Cu+Ni) ratios and metal tenors (Figure GS2023-9-5). This indicates that the sulphide (melt) in the Cartwright Lake intrusion may have been in equilibrium with a larger volume of mafic melts (i.e., higher R-factor), possibly without extensive early sulphide segregation. In contrast, mineralized gabbro intrusions (e.g., the Lynn Lake A plug and EL plug) show relatively lower metal tenors and (Pt+Pd)/(Cu+Ni) ratios, likely reflecting either sulphide segregation from a smaller volume of mafic (silicate) melts (e.g., Naldrett, 2004) or earlier sulphide segregation in a dynamic magmatic system.

Most of the Lynn Lake intrusion samples display (Pt+Pd)/(Cu+Ni) ratios <0.1, whereas the FLGC complex and the Cartwright Lake intrusion samples have ratios >0.1 (Figure GS2023-9-5)

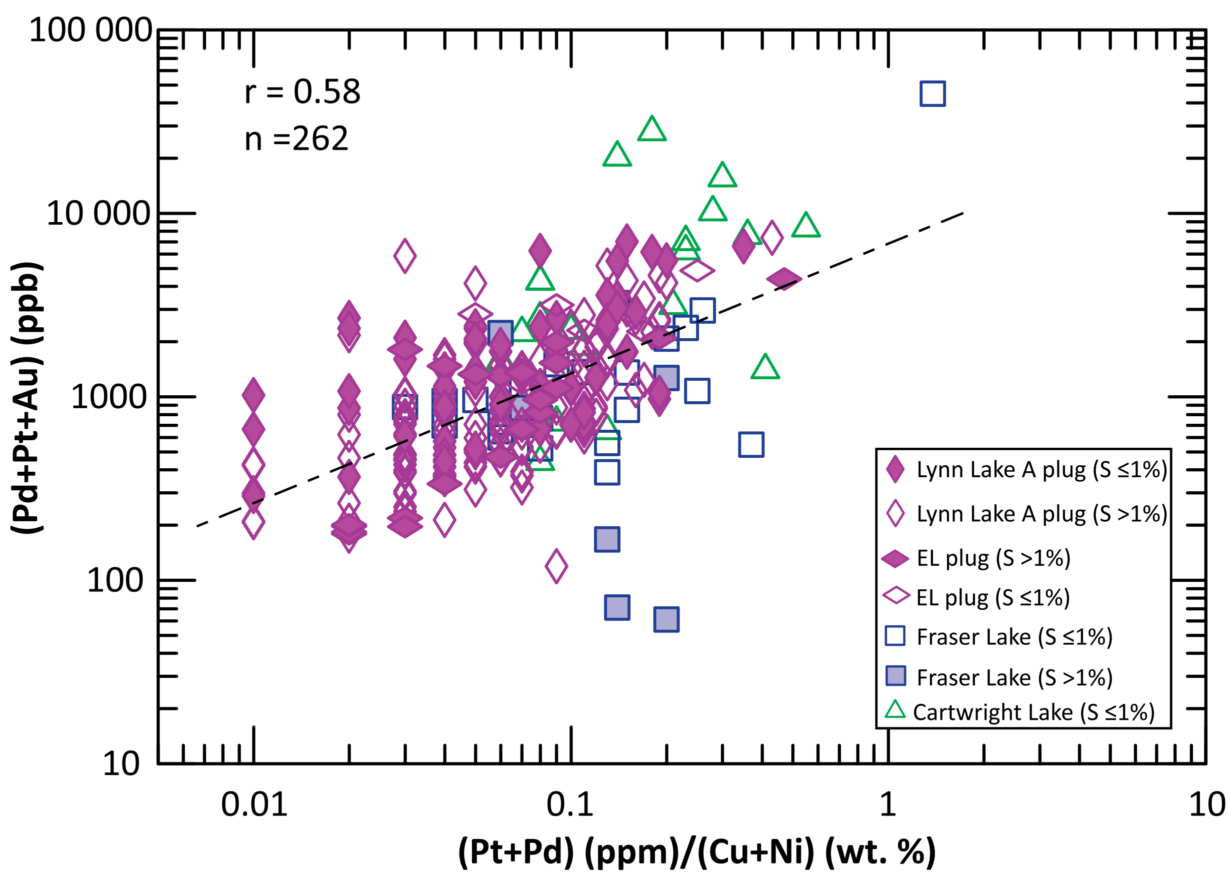


***Figure GS2023-9-5**: Diagram of metal tenors (Pt+Pd+Au) in ppb versus (Pt+Pd) in ppm/(Cu+Ni) in wt. % on the basis of 100% sulphide for gabbro intrusions in the Lynn Lake greenstone belt. Data from Peck et al. (2000). Calculation of metal tenors based on the formula in Barnes and Lightfoot (2005). Abbreviation: n, number.*

and higher metal tenors of (Pt+Pd), which suggests that there might not have been a significant segregation of sulphide melt from the mafic melts. On the other hand, a substantial amount of sulphides may have separated from the Lynn Lake mafic melts and concentrated at the base of the intrusion or the exit of the conduit/pathway connected to emplacement sites.

Highly siderophile elements (HSE)

Highly siderophile elements (HSE) include PGEs (osmium [Os], iridium [Ir], ruthenium [Ru], Pt, rhodium [Rh], Pd) as well as rhenium (Re) and Au (Lorand et al., 2021). The PGEs can be divided further into two subgroups: the iridium subgroup (IPGEs: Os, Ir, Ru) and the palladium subgroup (PPGEs: Pt, Rh, Pd). Not only do HSEs show strong affinity for a metallic iron phase but they are also strongly chalcophile and thus concentrate in a sulphide phase, when lacking the metallic iron phase in mafic-ultramafic systems (Rollinson and Pease, 2021). Therefore, HSEs together with chalcophile elements (Ni, Cu) whole-rock data are commonly used to investigate the fractionation and the state of sulphur saturation of mafic-ultramafic magmas and associated ore systems (Rollinson, 1993; Naldrett, 2004; Barnes and Lightfoot, 2005; Lorand et al., 2021; Rollinson and Pease, 2021; Orejana et al., 2023).

Seventy-eight bulk-rock and/or ore samples (Hulbert and Scoates, 2000) were analyzed for HSEs, which are evaluated and used to characterize PGE geochemistry of the Lynn Lake and Fraser Lake gabbroic intrusions. Based on S contents, these samples can be subdivided into two subgroups: unmineralized (S ≤1 wt. %) and mineralized (S >1 wt. %). Table GS2023-9-1 presents a summary of the data, revealing that the mineralized samples are relatively depleted in total (Σ) PGE concentrations (ranging from 27.2 to 222.1 ppb) and enriched in Co contents (i.e., averaging 855 ppm in the A plug and 410 ppm in the EL plug), when comparing with most major and giant magmatic Ni-Cu mineral deposits elsewhere (e.g., Naldrett, 2004). However, the unmineralized samples have abnormal ΣPGE contents of 9.4 to 53 ppb.

The HSEs with Ni and Cu data for the gabbroic rocks and associated ores (Hulbert and Scoates, 2000) in the LLGB are plotted in the order of their compatibility during partial melting of the mantle in Figure GS2023-9-6. It shows that the contents of less HSE-compatible elements (i.e., Au, Re, Pd) are higher and decrease in the direction of more compatible elements (i.e., Ru, Ir, Os), which suggests that the HSEs are controlled strongly by partial melting of the mantle. The most compatible element Ni and least compatible element Cu, both of which are attributed to chalcophile affinity, show much higher concentrations than the HSEs that had previously partitioned into the iron-nickel (Fe-Ni) core during differentiation from the mantle (Barnes and Lightfoot, 2005) and that were subsequently controlled by sulphide-silicate melts separation. The Ni-Cu deposits formed by the mantle-derived magmas tend to be depleted in PGEs relative to Ni and Cu, thus demonstrating a trough-shaped pattern in the primitive mantle-normalized profile, with typical positive steep HSE patterns of the gabbroic hosts (Figure GS2023-9-6).

According to Rollinson and Pease (2021), the primitive mantle-normalized (PM) ratio of $(Pd/Ir)_{PM}$ in mafic-ultramafic rock(s) can be used as a measure of the degree of fractionation during partial melting of the mantle, reflecting the fractionation between Pd (more incompatible) and Ir (more compatible) in PGEs. Most samples from the Lynn Lake intrusion and FLGC display enrichment of PPGEs over IPGEs indicated by $(Pd/Ir)_{PM}$ >1.0, which points to a lack of monosulphide solid solution in the residues during mantle partial melting. In this context, general positive correlation between Re/Os and $(Pd/Ir)_{PM}$ ratios (not shown), with a large range from 1 to 200 evident in the Lynn Lake intrusion (A and EL plugs), indicates that separation of monosulphide solid solution plays a key role (Lorand et al., 2021) in fractionating PPGEs from IPGEs in residual sulphide melts that formed Ni-Cu mineralization.

Platinum-group elements (PGEs)

Most of the samples with low S contents from the database (Hulbert and Scoates, 2000) were reanalyzed for a suite of elements (such as Pd, Pt, Au, S, Ni, Cu, Zn, Se, Te) by Peck et al. (2000). This review of the dataset confirms that the PGE content of the Lynn Lake samples is much lower than that of major to giant magmatic Ni-Cu-PGE deposits elsewhere (Naldrett, 2004; Barnes and Lightfoot, 2005). For instance, average ΣPGE content of 22 samples in the Lynn Lake A plug deposit is 222.1 ppb (Table GS2023-9-1), which is equivalent to 7.2 times the content of primitive mantle (Palme and O'Neill, 2014). As a comparison, average ΣPGE contents of those major to giant deposits (e.g., Naldrett, 2004) are 100 to 1000 times greater than that of primitive mantle.

Figure GS2023-9-7a shows that the Lynn Lake intrusion (A and EL plugs) is compositionally different from the FLGC based on Σ(PGE+Au) concentrations and (PPGE/IPGE) ratios. The Lynn Lake intrusion displays relatively high Σ(PGE+Au) values and less fractionation of PPGEs from IPGEs, which suggests that it may have been derived from a higher degree of partial melting of the mantle or formed by earlier phases of fractionating mantle-derived magmas. On the other hand, the FLGC contains lower Σ(PGE+Au) contents (<80 ppb; Figure GS2023-9-7b) with higher fractionation of PPGEs from IPGEs, likely reflecting an origin from a lower degree of partial melting of the mantle or derived from late phases of fractionating mantle-derived magmas. To determine which process was involved requires more precise age data because of the lack of field relationships for these two intrusions. Because their ages are identical within analytical uncertainties, the difference in timing between emplacement of the Lynn Lake intrusion (EL plug 1871 ±2.4 Ma) and that of the Fraser Lake (1870 ±6.2 Ma) intrusions could not be distinguished given the available age data (Turek et al., 2000).

Table GS2023-9-1: Average bulk-rock and ore sample geochemical compositions for the Lynn Lake and Fraser Lake gabbroic intrusions (data from Hulbert and Scoates, 2000).

Intrusion	Lynn Lake A plug				Lynn Lake EL plug		Fraser Lake gabbro complex			
Type	Unmineralized		Mineralized		Mineralized		Unmineralized		Mineralized	
	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD
n	5		22		22		23		6	
SiO_2 (wt. %)	50.14	2.13	27.72	19.20	40.60	6.32	49.06	1.94	37.02	17.46
TiO_2	0.23	0.04	0.17	0.15	0.21	0.09	0.58	0.69	0.34	0.21
Al_2O_3	7.04	4.51	3.70	3.66	8.29	3.00	16.49	3.65	11.71	7.01
$Fe_2O_3^T$	11.03	2.87	39.44	23.41	22.80	7.96	11.91	2.79	na	
MnO	0.17	0.05	0.11	0.06	0.14	0.04	0.17	0.04	0.13	0.08
MgO	20.28	5.67	9.69	7.83	12.84	4.75	11.25	4.37	8.03	6.73
CaO	6.56	3.42	4.48	3.40	7.33	2.22	9.05	1.95	5.50	4.01
Na_2O	0.64	0.72	0.38	0.45	0.71	0.33	1.64	0.66	1.05	0.65
K_2O	0.46	0.62	0.23	0.32	0.18	0.12	0.28	0.18	0.58	0.32
P_2O_5	0.04	0.01	0.03	0.03	0.04	0.04	0.17	0.28	0.09	0.06
S	0.44	0.23	18.19	14.95	8.34	4.89	0.45	0.21	10.85	14.57
LOI	0.54	0.23	18.52	14.72	8.48	4.88	0.67	0.29	10.92	14.56
Total	97.13		100.55		101.62		101.27		75.35	
V (ppm)	112	9	87	43	99	30	209	176	248	161
Cr	1582	701	786	524	747	543	339	290	297	388
Co	73	22	855	695	410	265	65	19	98	37
Cu	520	369	8362	6562	4732	2949	226	105	652	318
Ni	1324	606	26805	22280	10005	6056	358	241	1037	664
Zn	110	28	210	87	150	47	100	22	1175	1840
Se	1.3	0.8	39.9	27.3	15.2	7.5	0.7	0.4	1.7	0.4
Te	na		2.6	1.3	1.4	1.4	0.3	0.0	0.3	0.0
La	7.8	0.8	6.4	2.2	5.6	2.8	8.1	7.7	6.8	6.2
Yb	0.6	0.2	0.3	0.4	0.3	0.5	0.6	0.4	2.2	1.7
Nb	3.8	1.1	4.0	1.2	3.8	1.4	1.0	1.0	0.8	1.0
Th	0.0	0.0	0.0	0.0	0.2	0.5	2.7	1.9	18.7	23.6
U	0.0	0.0	0.1	0.4	0.0	0.0	0.5	1.0	10.8	15.4
Y	3.6	2.3	2.4	3.5	3.2	3.9	2.7	3.6	4.7	5.1
Zr	22.6	6.5	11.0	10.1	23.8	21.3	6.4	8.1	17.8	19.8
Rb	7.6	15.9	2.7	7.7	0.6	1.2	5.3	5.0	17.3	13.5
Sr	100.8	138.5	47.5	73.2	146.3	101.6	399.6	128.8	214.0	185.1
Ba	96.0	141.0	81.0	80.8	56.8	30.5	80.4	40.5	106.7	51.6
Os (ppb)	1.0	0.0	2.7	1.8	1.6	1.5	0.5	0.0	0.5	0.0
Ir	0.8	0.3	3.9	3.3	1.0	1.5	0.1	0.0	0.2	0.1
Ru	8.0	5.0	16.1	11.4	8.8	14.0	0.5	0.0	0.5	0.0
Rh	0.6	0.2	5.2	4.6	1.8	2.2	0.6	0.2	0.8	0.6
Pt	32.0	15.4	104.0	93.1	87.5	80.0	3.7	4.8	12.7	18.1
Pd	10.6	5.1	90.2	48.8	70.0	45.2	4.0	3.6	12.5	10.4
Au	12.4	4.7	42.6	32.3	49.4	34.3	6.1	2.7	18.7	19.6
Re	2.0	0.0	3.6	2.6	15.2	16.7	0.5	0.0	18.2	27.9
ΣPGE	53.0		222.1		170.6		9.4		27.2	
PPGE	43.2		199.4		159.2		8.3		26.0	
IPGE	9.8		22.7		11.4		1.1		1.2	
PPGE/IPGE	4.4		8.8		13.9		7.6		22.1	
Σ(PGE+Au)	65.4		264.7		220.0		15.5		45.8	

Data from Hulbert and Scoates (2000).
PGE, platinum-group elements (Ru, Rh, Pa, Os, Ir, Pt); IPGE: Os, Ir, Ru; PPGE: Pt, Rh, Pd.
Abbreviations: LOI, loss-on-ignition; n, number of samples; na, not analyzed; SD, standard deviation.

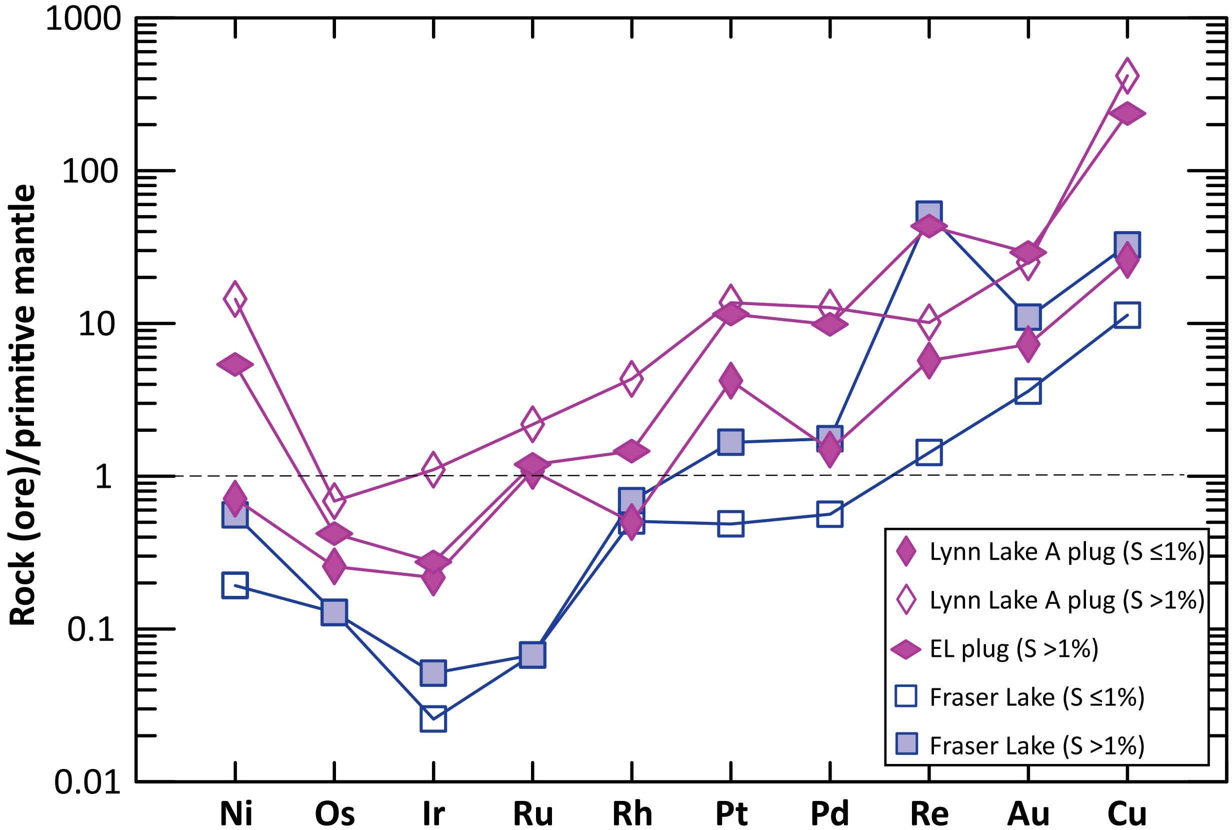


***Figure GS2023-9-6**: Diagram of primitive mantle-normalized highly siderophile elements together with contents of strongly chalcophile elements Ni, Re and Cu for mineralized and unmineralized gabbroic rocks in the Lynn Lake Ni-Cu deposit and the Fraser Lake gabbro complex. From left to right, the elements are arranged in order of decreasing mantle compatibility (after Rollinson and Pease, 2021). Data from Hulbert and Scoates (2000). Normalized values of primitive mantle from Palme and O'Neill (2014).*

Using MgO (wt. %) as a proxy for fractionation degrees of the mafic magmas versus the Σ(PGE+Au) values reveals that gabbroic samples of the Lynn Lake intrusion (A plug and EL plug) plot along a different trajectory from those of the FLGC, which are characterized by relatively lower concentrations of precious metals (<80 ppb) and lower MgO contents (Figure GS2023-9-7b). With an increasing degree of fractionation, Σ(PGE+Au) values appear to elevate in the Lynn Lake intrusion, whereas such values decline in the FLGC. This strongly suggests that different petrogenetic processes may have formed these two intrusions. Accumulative phases (e.g., olivine) are not likely involved before sulphide segregation from silicate melts in the Lynn Lake intrusion under dynamic environment conditions. In contrast, mafic-phase crystallization occurs simultaneously with sulphide separation from the magmas in the FLGC. Based on magnesium oxide (MgO) and Al_2O_3 contents, the FLGC is more evolved in chemical composition than the Lynn Lake intrusion (A and EL plugs; GS2023-9-7b). This observation is also supported by the fact that the FLGC contains relatively lower Ni and Co contents than the Lynn Lake intrusion (Table GS2023-9-1).

Sulphur- and oxygen-isotope compositions

Sulphur stable isotope composition of 53 bulk-sulphide samples reported in Hulbert and Scoates (2000) are plotted in Figure GS2023-9-8a to show the isotopic variation in three gabbroic intrusions of the LLGB (i.e., the Lynn Lake [A and EL plugs], Cartwright Lake and Fraser Lake). The distribution of $\delta^{34}S$ ratios in these intrusions are skewed to relatively lighter sulphur-isotope–composition values, with a mean value of 2.53 ±2.65‰. Most samples from the Lynn Lake intrusion (i.e., A and EL plugs) and the Cartwright Lake gabbro intrusion display a very narrow range of $\delta^{34}S$ ratios from 0.0 to 3.0‰, similar to typical mantle-derived mafic rocks (e.g., Rollinson and Pease, 2021). The FLGC shows a larger range of $\delta^{34}S$ values from 1.0 to 13.2‰, although mainly falling between 1.0 and 6.0‰. The $\delta^{34}S$ values indicate that the gabbros may have been affected by marine sedimentary rocks rich in heavy sulphur isotopes (up to 20‰) or contaminated by felsic rocks (e.g., Rollinson, 1993; Yang and Lentz, 2010; Rollinson and Pease, 2021). High Zn contents in mineralized gabbroic samples and massive sulphide ores (Table GS2023-9-1; Hulbert and Scoates, 2000; Peck et al., 2000) from the FLGC imply that the complex may have been contaminated (through assimilation) by VMS in the Wasekwan group.

Oxygen stable isotope composition of 41 bulk-rock samples (Hulbert and Scoates, 2000) also show a skewed distribution of the $\delta^{18}O$ values (Figure GS2023-9-8b), with a mean value of 6.9 ±1.2‰. Interestingly, the FLGC demonstrates a much smaller range in $\delta^{18}O$ ratios (5.5 to 7.0‰) than those of the Lynn Lake

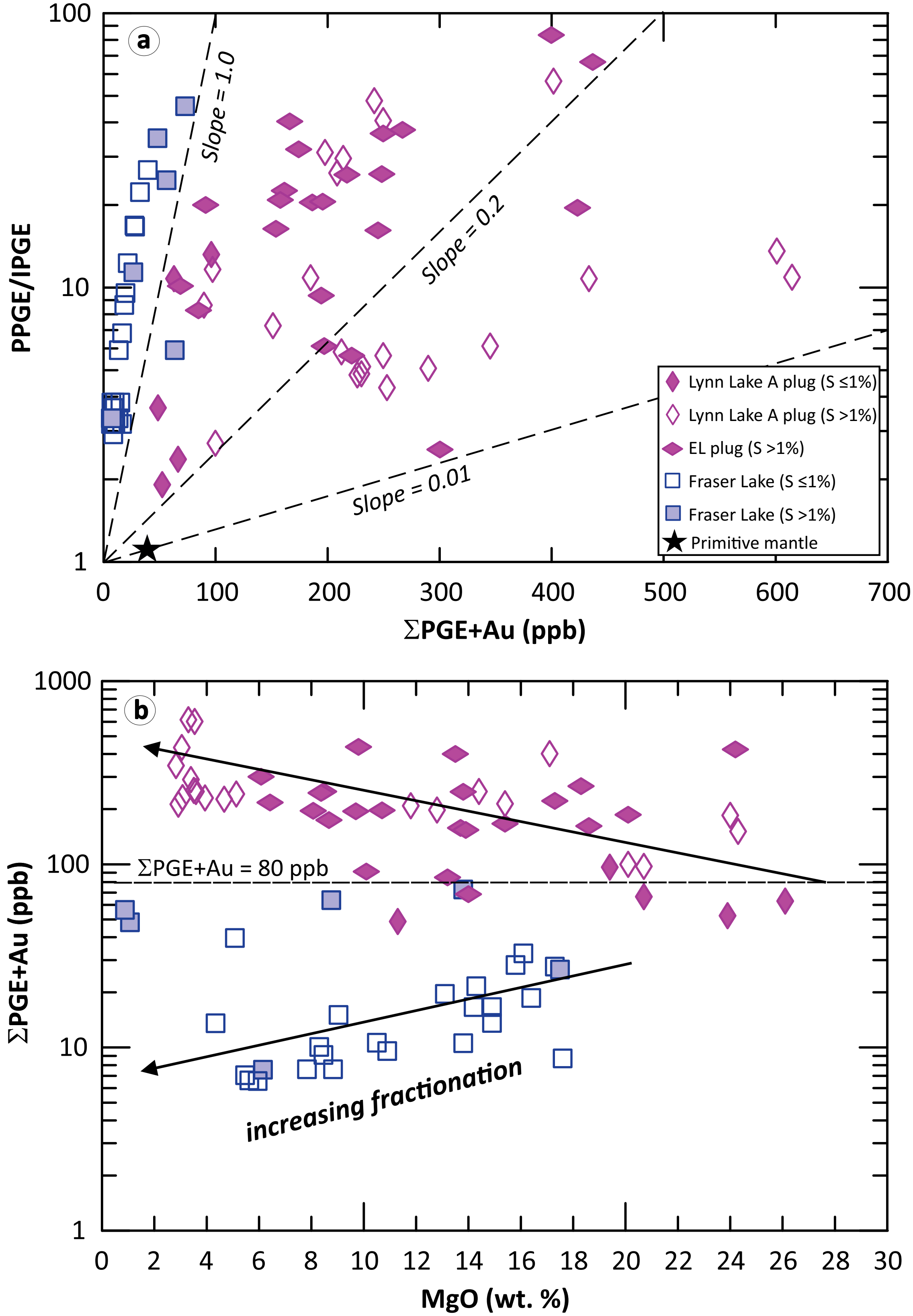


***Figure GS2023-9-7**: Discrimination diagram of geochemical data from the Lynn Lake and Fraser Lake gabbroic intrusions in the Lynn Lake greenstone belt, showing: **a)** Σ(PGE+Au) (ppb) contents versus (IPGE/PPGE) ratios and three dashed lines labelled slope equal to 1.0, 0.2 and 0.01, from left to right, indicating that fractionation between PPGE and IPGE decreases with increasing Σ(PGE+Au) concentrations; **b)** Σ(PGE+Au) (ppb) versus MgO (wt. %). Data from Hulbert and Scoates (2000). Values of primitive mantle from Palme and O'Neill (2014), with (IPGE/PPGE) ratio of 1.1, Σ(PGE+Au) content of 32.4 ppb and MgO of 36.77 wt. %. Abbreviations: PGE, platinum group element; IPGE, iridium platinum-group element subgroup (Os, Ir, Ru); PPGE, palladium platinum-group element subgroup (Pt, Rh, Pd).*

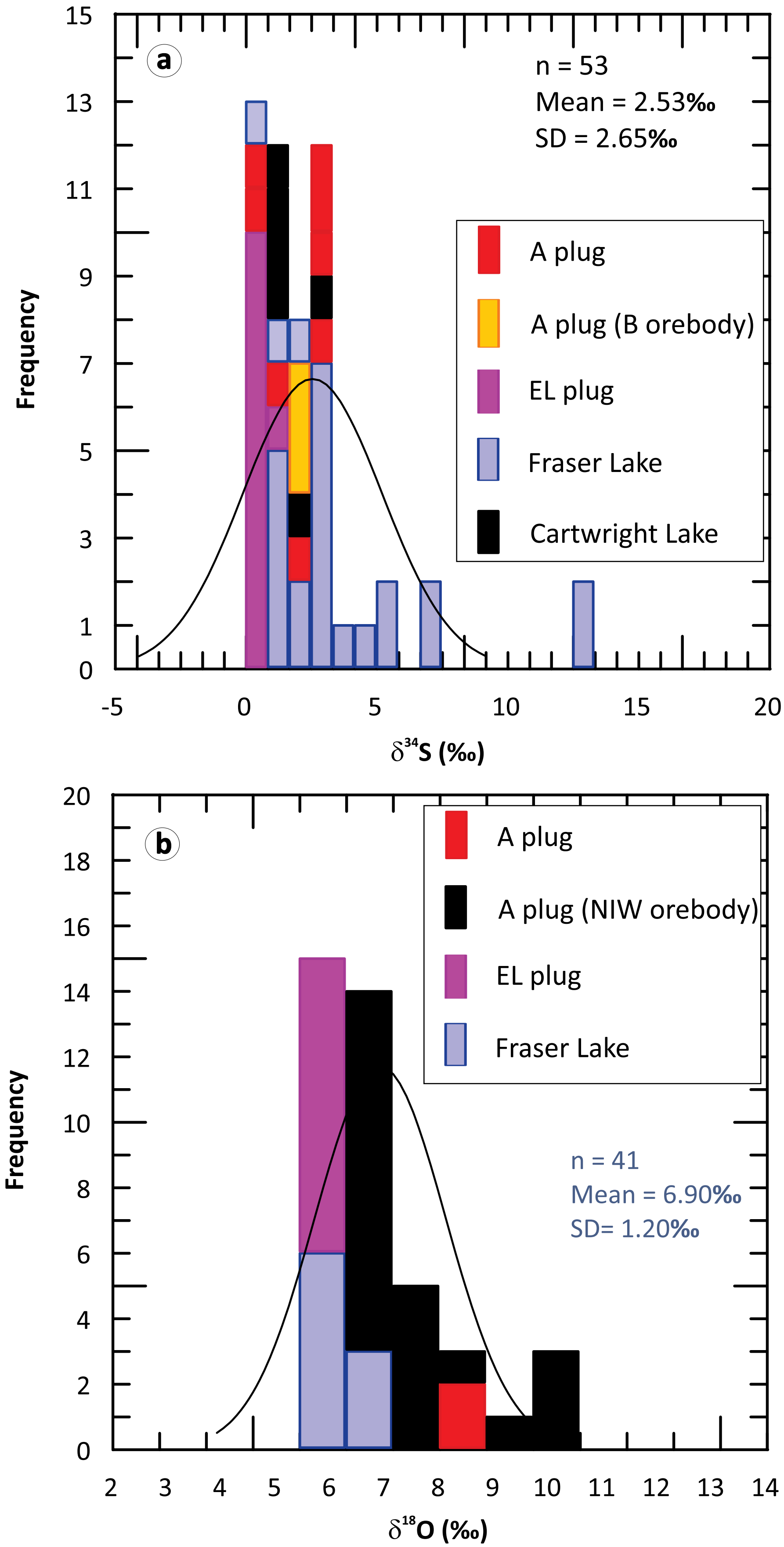


***Figure GS2023-9-8**: Histogram of **a)** sulfur-isotope composition (‰) and **b)** oxygen-isotope composition (‰) of bulk-sulphide samples from three gabbro intrusions in the Lynn Lake greenstone belt (data from Hulbert and Scoates, 2000). Abbreviations: n, number of samples; SD, standard deviation.*

intrusion (A plug and EL plug), mostly within the mantle value (5.7 ±0.2‰; Rollinson, 1993; Rollinson and Pease, 2021), which is consistent with a mantle-derived origin. In contrast, samples from the Lynn Lake A plug and EL plug show a large range of $\delta^{18}O$ values (5.5 to 10.0‰), which suggests that they may have interacted with low-temperature fluids, given that their $\delta^{34}S$ remains unaffected. These observations are consistent with the conclusion arrived at by Pinsent (1980), whereby hydrothermal activity may have locally remobilized sulphide ore and formed secondary sulphide veinlets in faults and/or fractures.

Economic considerations

Gabbroic rocks in the Lynn Lake intrusion host to Ni-Cu deposit and the FLGC are synchronous with the 1872.6 ±2.5 Ma A-type granites in the northern belt of the LLGB (Yang and Lawley, 2018), which suggests that these mafic and granite intrusions may have been emplaced into an intra-oceanic–arc extensional setting. Such an arc association at the Lynn Lake Ni-Cu deposit is underreported in the literature. There is likely a broader implication for how granitoid geochemistry (X.M. Yang and C.J.M. Lawley, work in progress) can track geodynamic transition(s) linked to the origin of VMS Cu-Zn, magmatic Ni-Cu and orogenic Au deposits in the Lynn Lake greenstone belt.

Gabbroic intrusions in the Lynn Lake greenstone belt are evaluated for fertility in terms of geological settings; field relationships; variation in lithologies and fabrics; and geochemical as well as S and O stable isotope features. Most gabbro intrusions display magmatic-arc signatures, but only some host magmatic Ni-Cu deposits. Crustal contamination of the mantle-derived mafic magmas appears to have triggered sulphide saturation and segregation in the magmas and mineralization systems. Sulphide-bearing Wasekwan sediments, and VMS deposits in particular, are potential candidates for providing external sulphur to the gabbroic intrusions. However, assimilation from the Wasekwan felsic volcanic to volcaniclastic rocks (e.g., Lynn Lake rhyolite) likely facilitates sulphide saturation in the intruding magmas. Cumulative mafic phases at contact zones seem to have higher potential to host Ni-Cu sulphide mineralization. A use of the PGE discrimination diagram (Figure GS2023X08-7) presented in this report demonstrates the difference between the Lynn Lake intrusion (A plug and EL plug) and the Fraser Lake gabbro complex, indicative of two distinct mineralizing systems.

Tube- and funnel-shaped orebodies evident in the Lynn Lake intrusion (i.e., A plug and EL plug) are probably the result of deformation (primarily D_2) from the original horizontal to a subvertical state. Therefore, structural analysis is a key to reconstructing the three-dimensional orientation of the intrusions and their hosted orebodies. However, it is likely that remobilization of the sulphide ores and redistribution may have taken place locally due to the deformation events(s) and metamorphism.

Acknowledgments

The author thanks W. Ezeana for providing enthusiastic field and laboratory assistance as well as for compiling some historical data; C. Epp and P. Belanger for thorough logistical support and processing of the samples; and H. Adediran and G. Keller for technical support. Thanks go to C.J.M. Lawley and M.G. Houlé of the Geological Survey of Canada for their collaboration and engaging discussions. The manuscript benefited greatly from constructive reviews by M. Rinne and T. Kennedy, technical editing by M.-F. Dufour and report layout by C. Steffano. Corazon Mining Limited is acknowledged for allowing field crew access to its property and drillcore; L. Hulbert and K. Wells are thanked in particular for guidance in core sampling; and Alamos Gold Inc. for providing their support.

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