Canadian Journal of Earth Sciences
Revue canadienne des sciences de la Terre

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Journal:	<i>Canadian Journal of Earth Sciences</i>
Manuscript ID	cjes-2016-0104.R1
Manuscript Type:	Article
Date Submitted by the Author:	10-Jan-2017
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Keyword:	Hearne Province, U-Pb Geochronology, Platinum group elements, Geochemistry, Mafic Intrusions

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Geology, U-Pb zircon geochronology and geochemistry of PGE-bearing Neoarchean and Paleoproterozoic gabbroic rocks of the Peter Lake Domain, southern Hearne craton, Canada

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Abstract

The Peter Lake Domain, a component of the Hearne craton in Saskatchewan, includes several intrusive complexes ranging in age from 2.70 to 1.83 Ga. Two gabbroic complexes (Swan River and Porter Bay) together represent one of the largest accumulations of Precambrian mafic intrusion, both metamorphosed at amphibolite facies. Sulfide-poor PGE occurrences are found in both complexes and share many textural and lithological characteristics with magmatic contact-type PGE-(Ni-Cu) deposits such as the chaotic Lac des Iles pluton and with layered stratiform deposits of large layered intrusions such as Bushveld or Stillwater.

Lithologically, both complexes are dominated by leucocratic gabbro and gabbro, locally characterized by cumulate layering, cross-bedding, brecciated and pegmatitic textures. U-Pb zircon crystallization ages between 2562 and 2560 Ma were obtained for the Swan River complex. Sulfide formation is interpreted to be of magmatic origin, rather than remobilized as had been speculated by exploration geologists, and is therefore of the same age as the host gabbro. Geochemical data support the interpretation of a mantle plume origin in a subduction environment for the Swan River Complex. The Porter Bay complex is much more restricted in areal extent and a leucocratic gabbro yielded a U-Pb zircon age of 1913 ± 1 Ma, which is interpreted as the crystallization age and the time of sulfide formation. Major and trace element geochemical data of Porter Bay complex rocks show a considerably more evolved character than the Swan River complex, and is interpreted as indicating emplacement in a continental arc environment.

Keywords: platinum-group elements; Peter Lake Domain, Hearne province; U-Pb zircon geochronology; geochemistry; mafic intrusions

Draft

Introduction

The Peter Lake Domain (PLD) of northern Saskatchewan (Macdonald and Thomas 1983) is host to one of the largest accumulations of mafic magmas in North America (Hulbert 1988). It is a $>5000 \text{ km}^2$ lozenge interpreted to represent the southeastern margin of the Hearne craton (Bickford et al. 1987, Stauffer and Lewry 1993, Rayner et al. 2005b) supported by limited geochronology, which identified Archean ages from felsic gneisses (Fig. 1) (Ray and Wanless 1980, Bickford et al. 1987, Rayner et al. 2005b). It is isolated from the contiguous Hearne basement by Paleoproterozoic metasedimentary rocks of the Wollaston Domain. The PLD is bound to the southeast by the Parker Lake shear zone and to the northwest by the Needle falls shear zone and Wollaston Domain. The Hearne craton, together with the Rae Craton, forms part of the Western Churchill Province and both became key components of Laurentia during the Trans-Hudson orogeny (e.g., Hoffman 1988, 1990, Berman et al. 2007, Pehrsson et al. 2013).

Regional bedrock geological mapping of the PLD in the late 1970s and early 1980s (Lewry et al. 1980, 1981, Stauffer et al. 1980, 1981, MacDonald and Thomas 1983) indicated that the area is largely underlain by weakly foliated felsic granitoids inferred to be Paleoproterozoic, with lesser components of felsic gneiss, mafic gneiss and undeformed mafic plutonic rocks largely inferred to be Archean (Bickford et al. 1987). Between 2002 and 2005, the domain was the focus of geological bedrock and surficial mapping projects, ground and airborne geophysical surveys, and targeted geochronological, geochemical and mineral deposit studies (Maxeiner and Hunter 2002, Maxeiner and Leatherdale 2003, Maxeiner et al. 2004, Campbell 2004, Maxeiner and Rayner 2005, Rayner et al. 2005a). Since their discovery in the early

1960s, several Cu-Ni-platinum-group element (PGE) mineral occurrences and deposits have been identified in the PLD (e.g. Maxeiner et al. 2011). Most of the early exploration work was focused on the southwestern part of the domain, particularly on the eastern half of the Love Lake pluton. Exploration shifted across the entire domain in the mid-eighties when anomalous PGE and Cu-Ni concentrations in the Swan Lake area (Fig. 1) were first recorded (Table 1). (Fig. 1). The aim of the present study is to investigate the PLD's mafic plutons, to better understand their extent, age and characteristics, to assess their mineral potential and to place them in an updated geological framework of the southeastern Hearne craton.

Over time, the PLD's geological framework has been significantly revised and new ideas about the timing, distribution, and mode of formation of its contained PGE-occurrences have been formulated (Maxeiner et al. 2011). Work by Corrigan et al. (2000) and Maxeiner et al. (2011) has revealed that the majority of the mafic rocks of the domain belong to two intrusive complexes, the 2.56 Ga Swan River complex and the 1.92 Ga Porter Bay complex. While the age, geochemistry and plate tectonic setting of the Porter Bay complex has been previously described (Maxeiner and Rayner 2011), a similar approach is required for the Swan River complex. The lithology, Cu-Ni-(PGE) mineralization, age, and geochemistry of the Swan River Complex will be investigated herein and through comparisons with the Porter Bay complex, the nature and age of mineralizing events will be assessed. These observations contribute to a better understanding of the magmatic history of the PLD and thus plate tectonic history of the southern Hearne craton.

Regional Geology

The dominant Neoproterozoic felsic plutonic rocks of the PLD consist of ca. 2.63 Ga (Bickford et al. 1987, Rayner et al. 2005b) tonalitic to granodioritic gneisses, primarily located in the northeast part of the domain along Reindeer Lake (Maxeiner et al. 2011). A minor component within these gneisses are screens of mafic volcanic¹ rocks that contain Mg-rich ultramafic sills, as well as separate units of iron formation, migmatitic pelite, and felsic volcanic rocks (Lewry et al. 1980, Ray and Wanless 1980, Corrigan et al. 2000, Maxeiner et al. 2010). Some of these supracrustal sequences might be correlative with the 2.72 to 2.68 Ga Rankin-Ennadai greenstone belt, exposed as outliers near the Saskatchewan/ NWT border, while others are 2.566 Ga (Maxeiner et al. 2010). Between 2.58 Ga and 2.54 Ga (Ray and Wanless 1980, Bickford et al. 1987, Annesley et al. 1992, Bickford et al. 2005), the tonalitic to granodioritic gneisses were intruded by an extensive suite of felsic plutons, previously referred to as the Lueza River granitoid suite (Stauffer et al. 1981, Maxeiner and Leatherdale 2003).

Abundant mafic plutonic rocks in the PLD were originally considered to be part of a single intrusive suite (Stauffer et al. 1981, Corrigan et al., 1999), referred to as the Swan River gabbro or the Swan River complex (SRC) (Corrigan et al. 2001). Based on geochronology and geochemistry, three distinct mafic intrusive complexes were subdivided, of which the SRC represents the volumetrically most abundant and oldest. It is dominated by recrystallized and foliated upper amphibolite-facies mafic plutonic rocks and has locally well preserved igneous layering and textures (e.g. Maxeiner and Leatherdale 2003). A U-Pb zircon age of a gabbro yielded an age of 2562 ± 4 Ma (Corrigan et al. 2001). A volumetrically less abundant

¹ As all of the supracrustal and most of the plutonic rocks in the Peter Lake Domain have been metamorphosed the prefix “meta-“ has been omitted in this paper.

(ca. 7% by area) intermediate to mafic intrusive suite is the 1.92-1.91 Ga Porter Bay complex (Maxeiner and Rayner 2011). It comprises a suite of gabbro, diorite, monzodiorite, and monzonite and was interpreted as having been emplaced in a continental arc environment along a north-dipping (present-day) subduction zone along the Hearne craton margin (Maxeiner and Rayner 2011). Rocks of the Porter Bay complex (hereafter PBC) and the remainder of the southeast Hearne craton margin were intruded by the 1.865-1.850 Ga Wathaman Batholith (Fumerton et al. 1984, Symons 1991, Meyer et al. 1992, Corrigan et al. 2000, 2001). Although the Wathaman Batholith, a continental arc complex, is predominantly made up of quartz monzonite and granite, it also contains a significant component of dioritic to mafic intrusive rocks, which are in part well layered (Maxeiner et al. 2004, Rayner et al. 2005a, Maxeiner and Rayner 2011).

In addition to these mafic suites, other components of the PLD include a suite of monzonite, quartz monzonite, monzodiorite, and quartz monzodiorite cutting the Swan River Complex in the southwestern part of the PLD (Maxeiner et al. 2011) dated at 2540 ± 1 Ma in one locality (Heaman et al. 2003). Preliminary incompatible trace element patterns of the suite suggest emplacement in an arc environment (Maxeiner et al. 2011).

The Campbell River group of the PLD (Lewry et al. 1980, MacDougall 1987, Maxeiner and Hunter 2002, Hunter 2003, Maxeiner and Rayner 2005) consists of an older succession of arenites and amphibolite, and a younger succession of argillite. The group (Figure 1) may be correlative with parts of the Wollaston Supergroup to the northwest of the PLD (Maxeiner et al. 2011), which records a ca. 2.08 Ga rifting event along the southeast margin of the Hearne craton (Fossenier et al. 1995, Ansdell et al 2000, Yeo and Delaney 2007).

The rocks of the PLD have recorded three ductile deformational events and at least two metamorphic events, including one proposed upper-amphibolite-facies event between ca. 2.55 and 2.53 Ga (Maxeiner et al. 2011), which overlaps within error with a $2566 \pm 23/-21$ Ma metamorphic event documented in the neighbouring Wollaston Domain (Annesley et al. 1992). Lower intercept ages for some of the felsic granitoid rocks of the domain between 1830 and 1800 Ma (Rayner et al. 2005b), growth of titanite at 1809 Ma (e.g. Annesley et al. 1992), and the low-grade metamorphic overprint recorded by the upper sequence of the Campbell River Group (Maxeiner et al. 2011), all indicate a lower amphibolite facies thermotectonic overprint during the Trans-Hudson orogeny. The Needle Falls and Parker Lake shear zones, which bound the southwest half of the domain along its northwest and southeast sides (Fig. 1), respectively, (Stauffer and Lewry 1993) were active between 1.85-1.77 Ga (Fedorowich et al. 2003).

Swan River Complex

As a result of the PLD mapping project (Maxeiner et al. 2004, Rayner et al. 2005a), the 2.562 Ga Swan River complex (SRC; Corrigan et al. 2000, 2001, Corrigan 2001) is now recognized as the most widespread of the mafic intrusive complexes identified in the domain (Maxeiner et al. 2011). The SRC stretches from the southwestern portion of the domain, where a component of it is referred to as the Love Lake pluton (Figs. 1, 2), to the Haglund Lake area northwest of Reindeer Lake, for an estimated strike extent between 120-190 km. It is dominated by mafic intrusive rocks, as well as minor anorthosite and ultramafic rocks and includes the Love Lake, Swan Lake and Reindeer Lake plutons. Many of the boudinaged mafic dykes within the older Archean granitoid basement are also likely related to the SRC.

Love Lake Pluton

One of the largest (20km x 5km) mafic intrusions that has been mapped in detail in the southwest PLD is the Love Lake pluton (Maxeiner and Hunter 2002, Leatherdale et al. 2003, Maxeiner and Rayner 2005 (Fig. 2). While intrusive contacts are not observed, based on the slightly older age of the surrounding granitoids (Annesley et al. 1992), it is interpreted to have been intruded into the 2.58-2.57 Ga Lueaza River granitoid suite. South of the Korvin Lake fault (Fig. 2), more highly strained and amphibolitized sheets of coeval diorite and gabbro are possible satellite intrusions of the pluton. Geophysically, the pluton is well defined by positive aeromagnetic and Bouger gravity signatures. The eastern half of the pluton is characterized by abundant breccia zones and hosts some of the most notable PGE occurrences of the domain (Table 1; Maxeiner and Rayner 2005).

Lithology and field relationships

The Love Lake pluton is dominated by strongly amphibolitized leucocratic gabbro. Minor components range from pyroxenitic to dioritic compositions. Cumulate layering (Fig. 3A) characterized by layers of anorthosite and gabbro alternating at 1-20 cm intervals is defined by variations in composition and/or grain size from pegmatitic to medium-grained. The majority of sulfide occurrences are located in the eastern part of the pluton (Fig. 2), where they are closely associated with cumulate layering near the contact with the older granite. Most occurrences of cumulate layering can only be traced for a few metres and are steeply dipping.

At several locations, the leucocratic gabbro contains abundant inclusions, which vary in size (decimeter to metre), in shape (angular to rounded), and in composition (mafic to

ultramafic) (Fig. 3B). These breccia zones are characterized by a coarse-grained to locally pegmatitic anorthositic gabbro to gabbro-norite matrix. Many of the inclusions in the western part of the pluton are of interpreted volcanic to subvolcanic origin and a few have a pre-existing foliation, suggesting that they were affected by a tectonic event prior to entrapment. Some of the more ultramafic inclusions are rounded and display reaction rims, likely indicating various stages of assimilation. On the basis of these observations, many of such inclusions are interpreted as xenoliths. There are also many breccia zones where the inclusions are of similar, or locally more mafic, composition with respect to the host rock, and they likely represent autoliths. In some cases the autoliths display internal cumulate layering.

Deformation within the Love Lake Pluton itself is generally very weak and a flattening fabric, defined by the alignment of amphiboles and amphibolitized pyroxenes, locally trends east-west, parallel to the main regional foliation. Where observed, igneous layering is also parallel to the main foliation. Disseminated sulfide blebs are generally also aligned within this foliation.

Petrography

The main Love Lake leucogabbro comprises plagioclase (labradorite), amphibole, minor relict pyroxene, biotite, magnetite, pyrite, and hematite. Generally the plagioclase forms 2 to 5 mm anhedral grains and most are of igneous derivation, but only some retain a hint of zoning, as a result of having recrystallized. Mafic mineral content of the leucogabbro varies considerably, but is most typically between 15 and 25%. The primary mafic silicate mineral assemblage is largely destroyed, with most of the pyroxenes replaced by hornblende and/or actinolite, with

minor local relict clinopyroxene (Fig. 4A). Petrographic and electron microprobe analyses of the leucogabbro (Leatherdale et al. 2003) suggest that least-amphibolitized leucogabbro contains both relict clinopyroxene and orthopyroxene, rimmed by hornblende and cummingtonite, respectively. This reaction was interpreted to represent an early, possibly Archean, metamorphic event. Other amphiboles recognized include aluminoferrotschermakite, tschermakite, ferrotschermakite, magnesiohornblende, and actinolite, all interpreted to be of metamorphic origin (ibid). A later lower amphibolite to greenschist grade metamorphic event, likely related to the Trans-Hudson Orogeny, is characterized by replacement of plagioclase by epidote, and of hornblende by actinolite, minor biotite (<5%) and chlorite. Magnetite typically accounts for at least 5% of the mafic mineral phases and is commonly partly hematized. Pyrite is ubiquitous, but rarely exceeds 1%.

Sulfides

There are a number of historic, trenched sulfide occurrences (Fig. 2) in the eastern portion of the Love Lake pluton (e.g. Saskatchewan Mineral Deposit Index² (SMDI) #538; #1844a; 1845; Fig. 2), all of which are in coarse-grained to varitextured gabbro, leucogabbro and pegmatitic gabbro. Two of these sulfide occurrences are situated near the contact with the older granitic rocks. Subtle cumulate layering, defined by thin sheets of melagabbro to pyroxenite, are found in close proximity to a small mineral exploration trench that forms part of locality SMDI 1845 (Fig. 2). In several instances, magmatic breccia zones of leucogabbroic to gabbroic rocks (Fig. 4B) contain up to 5% pyrrhotite and chalcopyrite. Such breccias may represent magma replenishment zones. In other PGE districts, such as in the Lac des Iles area,

² SMDI- Saskatchewan Mineral Deposit Index is a numbering system of all historic and new mineral occurrences and deposits of the Province of Saskatchewan. It can be accessed through a dedicated website (<http://www.economy.gov.sk.ca/Databases>) or geospatially online through the Geological Atlas (http://www.economy.gov.sk.ca/geological_atlas)

magmatic breccias are known to be important zones of mineralization (e.g. Barnes and Gomwe 2011). Similarly, the coincidence of breccia zones and sulfide occurrences in the Love Lake pluton is likely not coincidental.

In the best preserved examples, the sulfide mineral occurrences are characterized by a paragenesis of up to 5% disseminated to net-textured pyrrhotite-chalcopyrite (Fig. 4C). Minor pentlandite is exsolved within pyrrhotite crystals. Pyrite is present in a number of rocks and takes various forms. Locally, pyrite is the predominant sulfide phase accounting for 5-10% of the rock, with up to 2 mm large disseminated anhedral grains that are evenly distributed and overgrown by metamorphic amphiboles. Minor chalcopyrite and pyrrhotite are paragenetic with this coarse pyrite whereas rare small subhedral pyrite grains within pyrrhotite (Fig. 4D) are a result of retrograde reactions. The appearance of net-textured, chalcopyrite-pyrrhotite-dominated, blebby sulfides within pristine looking leucocratic gabbro (Fig. 4C), suggest an igneous origin to the sulfide mineralization.

Geochronology

All U-Pb age results presented here were determined using the isotope dilution–thermal ionization mass spectrometry (ID-TIMS) technique at the Geochronology Laboratories of the Geological Survey of Canada on single zircon grain or small multi-grain fractions (see Table 2 for details). Rock samples were prepared using standard methods of crushing and grinding followed by density separation to concentrate heavy minerals. Zircon grains were mechanically abraded (Krogh 1982) prior to dissolution of zircon in concentrated HF, extraction of U and Pb, and mass spectrometry following the methods of 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 2 with uncertainties reported at the 2σ level. Isoplot v. 4.15 (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.

A sample of typical leucocratic gabbro-norite (RM0301-115; GSC Lab No. z7880), as described above, was collected along Highway 905 (Fig. 2) in the western part of the Love Lake pluton. Within hundreds of metres of the sample locality, the gabbro-norite contains abundant mafic to ultramafic xenoliths, some of which are of interpreted volcanic origin and contain a pre-existing foliation. The sample is characterized by abundant subhedral, subophitic grains of plagioclase that are intergrown with largely amphibolitized pyroxene. As described above, two generations of amphibolitization are apparent. Interstitial magnetite greatly predominates over disseminated sulfides. The zircons recovered from the gabbro-norite are clear, colourless, faceted, prismatic, fracture- and inclusion-free crystals. Three overlapping, concordant zircon fractions (Fig. 5A; Table 02) give a crystallization age of 2562 ± 1 Ma (weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age).

This age confirms that the Love Lake pluton represents part of the 2.56 Ga SRC (Corrigan et al. 2001). It also suggests that, because of the interpreted magmatic nature of most of the PGE occurrences hosted by the Love Lake pluton (see previous section), 2562 Ma is a good approximation for the age of mineralization.

Swan Lake pluton

An approximately 0.5 x 3 km ellipsoid, zoned and transposed gabbroic intrusion, south of the northeastern bay of Swan Lake (Fig. 1; Fig. 6), cuts older granitoid rocks and, when it was first mapped, was interpreted to form part of the SRC (Maxeiner and Leatherdale 2003, Maxeiner and Rayner 2005). Similarly to the Love Lake pluton, it intrudes granitoid basement of the Hearne craton (ca. 2.63 Ga granodiorite-tonalite migmatite complex, and 2580-2570 Ma Lueza River granitoid suite). The pluton coincides with an aeromagnetic high, caused by a more magnetite-rich, finer-grained margin and less magnetite-rich central zones consisting of homogeneous gabbro and a brecciated gabbro.

Lithology and field relationships

The central portion of the Swan Lake pluton, approximately 200 m in diameter, is composed of a medium-grained to pegmatitic (i.e. varitextured) gabbro to leucogabbro. It is commonly characterized by the presence of abundant subrounded to subangular gabbroic and ultramafic autoliths between 30 and 70 cm in diameter (Fig. 7A), and comprising up to 70% of many of the outcrops. The leucogabbroic matrix is massive to weakly foliated and locally sulfide bearing (Fig. 7B).

Surrounding the central brecciated gabbro is a more extensive (0.4 x 1.4 km) equigranular, homogeneous and massive gabbro, which is generally coarse grained and locally pegmatitic or varitextured. The marginal phase of the Swan Lake pluton consists of an approximately 100 m wide, weakly to moderately foliated microgabbro, which is strongly magnetic and locally plagioclase-phyric (Maxeiner and Rayner 2005). Foliated granite xenoliths are locally present within the marginal zone.

A second gabbro intrusion in the Swan Lake area is located three kilometres to the south (Fig. 6) and contains spectacularly well-preserved igneous features, including trough cross-bedding, rhythmic zebra-layering, and variotextured gabbros. Unlike the Swan Lake pluton, this intrusion has no known economic mineral occurrences associated and the rocks do not contain sulfides or magnetite, but based on physical proximity and lithological similarities the two intrusions are considered to be correlative (Maxeiner et al. 2011) and samples from it were included in the geochemical evaluation.

Petrography

The main gabbroic to leucogabbroic central phase of the Swan Lake pluton contains subhedral, locally saussuritized plagioclase ($\sim\text{An}_{70}$), and hornblende, which forms millimetre- to centimetre-sized irregular patches within the plagioclase matrix. Where together, the hornblende, which is interpreted as metamorphic, appears to overgrow pyrrhotite. Local gabbro phases are characterized by poikilitic pyroxene crystals, up to 2 cm in diameter and are mostly amphibolitized. Magnetite is a very common and abundant accessory mineral; apatite and titanite occur in varying proportions. Magnetite appears to have crystallized before the sulfides as it is contained as inclusions within them.

A pyroxenite along the transition between the central gabbroic phase and the homogeneous and massive gabbro phase (sample RM0501-075) is highly amphibolitized, with the majority of pyroxene having been replaced by abundant tremolite-actinolite. Judging by the calcium-rich nature of the amphiboles, the pyroxenes that were replaced were likely clinopyroxene. Relict orthopyroxene was identified in one sample of ultramafic rock (sample RM0501-074)

and is replaced along its margins by various amphiboles. Many of the amphiboles and biotite are in turn replaced by late, magnesium-rich chloritic phases. Sulfides are lacking in the ultramafic rocks.

Sulfides

In 2004 and 2005 a number of mineral exploration trenches constituting the Swan Lake Pt-Pd-Ni-Cu showing (SMDI 1896; Fig. 6), which is located at the southern contact between the leucogabbro breccia and the surrounding gabbro, were investigated. One of the main historic exploration trenches exposes a succession of brecciated gabbros that pass southwestward into relatively homogeneous melagabbro and ultramafic rocks over a distance of about 20 m. Disseminated millimetre-sized pyrrhotite, chalcopyrite, and pyrite are present throughout but become more prevalent towards the southern end and are generally most abundant in the varitextured to pegmatitic zones. The south end of the trench is in a pyroxenitic rock with abundant disseminated sulfides, but varitextured to pegmatitic gabbro is also present.

Locally, sulfides are associated with centimetre-scale cumulate gabbroic layering, and in one case such layering may extend 25m along strike to another area of demonstrable igneous layering. Cumulate layering was also observed in autoliths contained within the central brecciated zone of the pluton.

A heavily mineralized varitextured to pegmatitic gabbro is characterized by the presence of millimetre-sized, polymineralic sulfide blebs (Fig. 7C) that are interstitial to subhedral plagioclase grains ($\sim\text{An}_{70}$). The blebby sulfides are dominated by pyrrhotite–chalcopyrite with minor pentlandite (Fig. 7C, D) and rare subhedral pyrite crystals, the latter of which overgrow

the chalcopyrite or pyrrhotite (Fig. 7D). The pyrite most likely formed in response to sulfur release from pyrrhotite during retrograde cooling following the peak of metamorphism (Craig and Vokes 1993). The blebby, disseminated nature of the pyrrhotite and chalcopyrite (Fig. 7C,D) is consistent with having formed from an immiscible sulfide liquid as part of the crystallization process of a mantle-derived mafic silicate melt (e.g. Eckstrand and Hulbert 2007).

Geochronology

A sample of a coarse-grained to pegmatitic, massive, sulfide-bearing gabbro (RM0401-039; z 8487) was collected from the southern end of SDMI 1896 (Fig. 6) and thereby represents a component of the central leucogabbroic breccia zone of the pluton. The sample is richly mineralized, containing abundant disseminated pyrrhotite with minor exsolved pentlandite, and chalcopyrite, which based on the previously described textural relationships are interpreted as being magmatic in origin.

Three TIMS fractions (two multi-grain, one single grain) of clear, colorless, anhedral zircons yielded an upper intercept age of 2562 ± 3 Ma (Fig. 5B), which is interpreted as the time of emplacement and crystallization. This age is identical to that of a pegmatitic gabbro from north Reindeer Lake (Corrigan et al. 2001) and to the Love Lake leucocratic gabbro (sample RM0301-115 described herein), and confirms that the rock is a component of the 2562 Ma SRC. As the observed petrographic textures point to a magmatic origin for the sulfides, this age is also interpreted as the time of sulfide formation.

Other Swan River complex plutons

Mafic plutons inferred to be part of the SRC possibly span as much as 190 km along strike, from southwest of Highway 905 to the Saskatchewan-Manitoba border (Fig. 1). A few intrusions along the northwest shore of Reindeer Lake are briefly reviewed here.

Lithology and field relationships

Generally the dioritic to gabbroic intrusions west of Reindeer Lake, between Swan Lake and Patterson Island (Fig. 6) are largely recrystallized and extensively invaded by gabbroic-dioritic, monzonitic, and later granitic intrusive suites (1.92 Ga PBC and 1.86 Ga Wathaman Batholith). Igneous layering and breccia zones are locally preserved. Local melagabbroic, pyroxenitic varieties, and anorthositic components also exist.

Between Patterson Island and Feaviour Peninsula (Fig. 1), numerous small gabbroic to noritic intrusions are found cutting the granodiorite to tonalite basement. This is the sample locality that yielded the only previous age for the SRC, 2562 ± 4 Ma from a pegmatitic mafic intrusion, (Corrigan et al 2001). Well -preserved examples of rhythmic layering (Fig. 8A) and zones where pegmatitic gabbro selectively replace some of the layering (Fig. 8B) are well exposed in large lakeshore outcrops. Zones of pegmatitic gabbro (Fig. 8C) are emplaced conformably to rhythmic layering (Fig. 8B), but also locally cross-cut the layering (Fig. 8D).

To the north of Feaviour Peninsula, a number of dioritic to gabbroic plutons extend as far east as the Saskatchewan-Manitoba border. On the basis of textural observations and the level of recrystallization, many of these are interpreted to form part of the SRC.

Petrography

The mafic plutonic rocks in the Reindeer Lake area are generally equigranular and massive to moderately foliated, with local relict ophitic to subophitic textures (Maxeiner and Leatherdale 2003). Secondary textures include pyroxene replacement by hornblende, porphyroblastic hornblende, strong sericitization of plagioclase, and new growth of Na-rich plagioclase, likely metamorphic. Accessory minerals include epidote, magnetite, pyrite and titanite, as well as the local presence of sulfides.

Sulfides

Two small exploration trenches exposing minor quantities of disseminated, millimetre-sized chalcopyrite, bornite, covellite, pyrite and lesser pyrrhotite make up the Haglund gabbro Cu-Pt-Pd showing (SMDI 1845b; Fig. 1). Gabbroic rocks in the immediate vicinity of the Cu-PGE showing vary from homogeneous to heterogeneous, and are characterized by variable grain size and mafic mineral content. Coarse-grained to pegmatitic, in part varitextured, gabbros grade into megacrystic diorite or leucogabbro. Disseminated sulfides occur preferentially in the coarse-grained gabbroic phases and are accompanied by appreciable amounts of magnetite, which is otherwise absent from the Haglund gabbro. Pyrite occurs on faults and minor shear planes; malachite on late fractures.

Geochronology

A sample of Wiley Bay leucogabbro (RM0301-108; z7879) was collected on north Reindeer Lake, southwest of Patterson Island (Fig. 1, 6); the rock in this location is very similar in appearance to the Love Lake leucogabbro (RM0301-115) and also features centimetre-scale rhythmic layering, as well as local breccia zones containing abundant autoliths. The intrusion

postdates surrounding units of mafic volcanic rock and pelite, and is itself cut by the Patterson Island pluton to the northeast and by the Wathaman Batholith to the southeast.

Abundant, large, colorless to pale brown anhedral and fragmental zircon grains were recovered. A weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of three TIMS fractions (one concordant and two discordant) yielded an age of 2560 ± 3 Ma (Fig. 5C; Table 02), interpreted as the time of crystallization of the pluton and a lower limit for the age of the supracrustal rocks. This result is within error of the U/Pb zircon ages obtained in this study for the Love Lake and Swan Lake plutons and suggests that all were emplaced during a relatively tight time frame between 2562-2560 Ma.

Swan River complex geochemistry

Wholerock geochemical data of 36 samples (Supplementary data Table S1) were utilized for the characterization of the mafic to locally ultramafic plutons of the domain, in order to assess their petrogenetic nature and lithotectonic environment of formation. For presentation and discussion purposes we have subdivided the data for the SRC into four groups, based on their physical location or association. The first group includes twelve samples from the Reindeer Lake area (Fig. 1). The second group is from the Swan Lake-Campbell Lake area and is mostly derived from two separate plutons and some isolated intrusions, consisting of eight samples. The third group consists of eight samples from the Love Lake pluton, which is located north of Warner Lake. The fourth and final group is also from the Warner Lake area and consists of isolated intrusions located south of the Love Lake pluton (Fig. 1 and Fig. 2). As a caveat, many of the samples collected are of cumulate, pegmatitic or porphyritic rocks, none of which can be representative of the true bulk composition of the host pluton or suite.

In order to make predictions about the parental magma, rapidly chilled magmas (i.e., fine-grained) are the most desirable sample targets; however no such unequivocal chilled magmas were encountered during this mapping project and therefore the following interpretations might be influenced by cumulate processes. All samples were processed for major, trace and rare earth elements by Activation Laboratories in Ancaster, Ontario by ICP mass spectrometry.

Major and trace elements

Whole rock analyses of major and trace elements (Supplementary data Table S1) of these four SRC suites are generally consistent with basaltic compositions (e.g. low Zr/TiO₂ concentrations relative to Nb/Y). Most of the major element concentrations are remarkably consistent between the four suites, suggesting that they are geochemically similar and related to a single magmatic pulse affected by fractional crystallization (Fig. 9).

SiO₂ concentrations vary from 41-56 wt% with the majority of analyses falling between 48 and 52 wt%, displaying a coherent trend when plotted against Zr. With increasing Zr, elements such as MgO, CaO, Ni, Cr, and to a lesser extent Fe₂O₃ decrease, suggesting that olivine and clinopyroxene were likely crystallizing phases during the petrogenesis of the rocks. Likewise, increasing K₂O, Y, La, Nb, and Th with increasing Zr, are consistent with a suite of igneous rocks that are related to each other through fractional crystallization processes.

To further test the idea that the rocks of the four suites formed as a result of the same igneous crystallization process, a Pearce element ratio plot was constructed, using Zr as the conserved

element and as the denominator (Fig. 10). When Fe, Mg, Ca, Al and Na are plotted against Si, it becomes apparent that all SRC samples are well correlated with a slope of approximately one, which suggests that crystallization of these three minerals was involved during crystal fractionation (Fig. 10). If any other phase containing Mg, Fe or Si was involved during the crystallization process the data would depart from the line (Fig. 10). The slight deviation of the Swan Lake suite data from the olivine-plagioclase-clinopyroxene tie line might be due to fractionation of a Ca-poor pyroxene, consistent with the fact that many of the Swan Lake samples contained some minor relict orthopyroxene and their CIPW-norm calculations (not shown), which indicate that samples of the SRC are dominated by Ca-rich plagioclase clinopyroxene, orthopyroxene and olivine.

Rare earth elements and Pd-Pt concentrations

The extended trace element patterns of the SRC suites (Fig. 11) are all quite similar, with relatively elevated but flat La to Nd concentrations and distinct negative high-field strength element (HFSE; Nb, Zr, Ti) anomalies. The suites are further characterized by slightly positive Eu anomalies and variable, weak Ti anomalies (Fig. 11). On a diagram of Sm/Y versus La/Sc the SRC has relatively low ratios of both these element pairs (Fig. 12)

For samples of the SRC, Ni, Cu and Pt correlate reasonably well with sulfur, which would suggest that a sulfide liquid controlled the distribution of these elements (Fig. 13). No correlation exists between Pd and S for samples of the SRC (Fig. 13C).

The average Pd/Pt ratios of 21 analyses of the SRC is 1.5 (Fig. 13F), with a relatively narrow range between 1 and 3. There is no increase of Pd/Pt ratios with increasing Pd and the values

are slightly higher than those for mantle-derived magmas (Maier and Barnes 2004). Ratios of mantle concentrations of these metals are generally about 0.5 (Fig. 13F).

Cu/Pd ratios of samples from the SRC show considerable scatter between about 100 and 100 000, which compares well with early leucocratic rocks from the Lac des Iles intrusion (Fig. 13E) and is somewhat enriched over original mantle concentrations.

Porter Bay complex

In a field-based study that was augmented by geochronological and geochemical data, Maxeiner and Rayner (2011) identified a 1917-1913 Ma gabbro–monzodiorite–monzonite suite in the Patterson Island area of the PLD (Fig. 1). The plutonic suite, which cuts the SRC and surrounding older granitoid gneisses of the Hearne craton, is also characterized by the presence of a variety of volcanic and subvolcanic inclusions that are of similar age to the host intrusion. Geochemically, the rocks were classified as calc-alkalic to alkali-calcic, metaluminous and variable from ferroan to magnesian (ibid). On the basis of fractionated trace element patterns and negative high field strength element anomalies, the PBC was interpreted to have been emplaced along a destructive plate margin, most likely as a continental arc along the southeastern margin of the Hearne craton. In this paper we present additional observations and data in relation to the sulfide occurrences and the age of mineralization of the PBC, in order to contrast and compare them those of the SRC.

Sulfide Occurrences

The Patterson Island pluton of the PBC (Fig. 1, 6) hosts one of the most notable PGE occurrences of the PLD. The Antoine's Cu-Ni-Pt-Pd showing (SMDI 2374, Fig. 6), west of

Patterson Island, is characterized by disseminated chalcopyrite-pyrrhotite found within the gabbroic to leucogabbroic margin of the zoned pluton. Historic grab samples collected from mineral exploration trenches related to SMDI 2374 returned particularly high concentrations of Pd (Table 1). Similar, but less PGE-rich mineralization is also known in the 'Ant' Lake area (SMDI 2373, Fig. 6) and other parts of the Patterson Island pluton. Both occurrences are hosted in the relatively homogeneous and massive, yet strongly amphibolitized west central part of the intrusion. Zones of brecciation and cumulate igneous layering are present in the general vicinity of the occurrences, which are characterized by less than five percent disseminated pyrrhotite and chalcopyrite, as well as some fracture-filling pyrite. Several other PGE-bearing sulfide occurrences are located near zones of magmatic breccias and pegmatitic gabbros (Maxeiner et al. 2004). The disseminated to blebby texture of the sulfide minerals observed in samples of mineral occurrences from the Patterson Island pluton (Maxeiner et al. 2004) is again consistent with having formed from an immiscible sulfide liquid.

Geochronology

The age of the PBC (Maxeiner and Rayner 2011) is further constrained with an additional, rhythmically layered sample collected for U/Pb geochronology (RM0401-036) from the 2x5 km large leucogabbroic marginal phase of the Patterson Island pluton. The same leucogabbro phase is also host to most of the pluton's PGE-occurrences (Fig. 6), including the Antoine PGE occurrence (Table 1). The central monzonitic to monzodioritic phase of the pluton, postdates the gabbroic rocks.

Zircons recovered from the Patterson Island leucogabbro sample are typically clear, colorless, anhedral fragments (Fig. 14). Three single-grain fractions of zircon were analysed by TIMS

(Table 2). Though slightly discordant (0.2%), all fractions overlap (Fig. 14) and give a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1913 ± 1 Ma, interpreted as the crystallization age of the pluton. Because of the magmatic nature of the sulfide occurrences that are hosted by the leucogabbroic intrusion, the age is also interpreted as the age of sulfide formation. This is identical in age with a 1913 ± 2 Ma age for a megacrystic monzodiorite also from Patterson Island (Maxeiner and Rayner 2011) and is consistent with field observations that the leucogabbro is one of the youngest phases of the 1917-1913 PBC.

Discussion

Extent of the mafic complexes of the Peter Lake Domain

This study has established that the age of the Swan River complex is 2562-2560 Ma and that this Neoarchean intrusive complex is extensive within the PLD (Fig. 1). The Love Lake pluton (ca. 5x20 km) represents one of the SRC's biggest contiguous mafic intrusions, but identically-aged plutons have now been identified along strike about 70 km, 100 km and even 130 km farther to the northeast. The extent of this Neoarchean mafic complex alone makes the PLD one of the most significant mafic terrains in Canada.

In relation to other important mafic plutons in the world, the surface extent of the Love Lake pluton alone is intermediate between the Skaergaard Intrusion (ca. 7.5x11 km) and the Stillwater Complex (8x47 km). Locally, the footprint of the SRC is much bigger than that of the 600 Ma younger PBC, which has two main intrusive centres, the Patterson Island pluton at about 55 km² being the bigger of the two.

Geochemical Distinction of Mafic Plutonic Rocks

The PLD's mafic intrusive complexes share many textural and lithological features rendering them difficult to distinguish in the field. Therefore, initial distinction was primarily achieved through the use of geochronology. However, whole-rock geochemistry subsequently brought to light a number of criteria that have enabled distinction:

- Gabbroic rocks characterized by low La/Sc and Sm/Y ratios (Fig. 12) and multi-element patterns that lack negative Ti anomalies (Fig. 11) are probably part of the SRC.
- Gabbroic rocks with low La/Sc and Sm/Y ratios (Fig. 12) and negative anomalies of all HFSE (including Ti) are related to the Wathaman Batholith.
- Gabbroic rocks with high La/Sc and Sm/Y ratios (Fig. 12), coupled with negative HFSE anomalies are probably part of the PBC.

The significant geochemical difference between SRC and PBC suites is likely reflective of them having been emplaced within different lithotectonic environments. The relatively low Sm/Y ratios (Fig. 12) of the SRC magmas coupled with overall less evolved trace element signatures (Fig. 11), likely suggests an extensional setting.

Micro-Rhythmic Layering and Magmatic Processes

Spectacular examples of micro-rhythmic and trough cross-bedded layering in the SRC and PBC rocks (Fig. 15), where melagabbroic bases alternate with anorthositic tops to form couplets, are identical to the world-class Skaergaard and Stillwater intrusions. This suggests that a similar process (McBirney and Noyes 1979, Irvine et al. 1998) was at work to form the PLD mafic intrusions. Planar micro-rhythmic layering is the more common type of igneous layering in the PLD (Fig. 15A), is traceable for tens of metres, and likely formed in response

to fractional crystallization in combination with slow moving convection currents. In the PLD, less common metre-scale stacks of layered gabbro-anorthosite couplets are truncated repeatedly along angular unconformities (Fig. 15B, C) suggesting that, similar to the Skaergaard intrusion (Irvine et al. 1998), periodic density currents may have deposited a crystal mush near the base of the intrusion. Repeated cycles of convection and density surges in some of the PLD mafic intrusions, led to the formation of multiple sets of denser mafic bases and lighter plagioclase-rich tops just as described in the Skaergaard example (Irvine et al. 1998). Using the Skaergaard example, it seems plausible that cross-bedded layering, where observed in PBC and SRC plutons, formed near the base of the intrusion, whereas planar microrhythmic layering formed along the wall of the intrusions.

An alternate way of explaining the presence of micro-rhythmic cumulate layering, referred to as *inch-scale layering* in the Stillwater Complex (e.g., Page 1979) and also observed in Archean anorthosite-leucogabbro complexes (e.g., Polat et al. 2010), is the mechanism of *crystal aging* as proposed by Boudreau (1995). Crystal ageing is speculated to have formed in sufficiently large mafic intrusions as a result of processes within the crystal-mush, possibly because of fluid escape and flux melting. On the basis of numerical modeling (ibid), the process leading to the formation of doublets of centimetre-scale mafic and felsic layers is thought to be similar to that of Liesegang formation. It is described to result mainly from post-nucleation processes that affect the crystal mush and occur when crystals at the margins of a developing layer grow at the expense of those in the centre, thereby leading to further refinement of already existing igneous crystallization textures. Such processes appear to be restricted to large plutons in which extensive, long-lasting crystal mush zones and strong thermal and chemical gradients persist for millions of years.

Geochemical data of the SRC are consistent with the magmas having been derived from a mantle source during a single phase of plutonism and subsequent fractional crystallization. Ca-rich plagioclase, clinopyroxene, orthopyroxene and olivine have been shown to be the main crystallizing silicate phases (Fig. 10). Because Ni, Cu and Pt correlate reasonably well with sulfur (Fig. 13), it is suggested that a sulfide liquid controlled the distribution of these elements. The PLD mafic intrusions exhibit modal layering textures that are consistent with having formed as a direct result of primary magmatic processes as described by Irvine et al. (1998), [or Polat et al. \(2010, 2011\)](#), but fine-scale doublets of mafic and felsic layers are likely the result of secondary enhancement processes such as described by Boudreau (1995).

Late-Stage Magmatic Processes

Presence of metamorphic amphiboles in both PLD mafic complexes suggests that similar to the Bushveld and Stillwater complexes (Boudreau 1995, 2002), the magmas that formed the Peter Lake intrusions must have contained water, or [were](#) subjected to influx of water during the late stages of crystallization or during metamorphism. Similar to the Lac des Iles deposit (Sutcliffe et al. 1989, Barnes and Gornall 2011) and to features observed at the Skaergaard intrusion (Andersen et al. 2006), many areas in the PLD are characterized by the presence of pegmatitic and varitextured rocks (Fig. 8B, C) that are in part concordant to the cumulate layering but also slightly oblique to it or cross-cutting (Fig 8D). Such rocks can form when magma becomes fluid saturated and when that fluid moves into areas of the pluton that are not yet fully consolidated, where it induces flux-melting. At Lac des Iles, such features have been interpreted to have played a role in the formation of the deposit and the enrichment of Pd (e.g.

Hinchey et al. 2005). A study testing this hypothesis (Barnes and Gomwe 2011) found, however, that pegmatitic and varitextured rocks had the same geochemical signature as the rest of the Lac des Iles pluton and that a fluxing agent did therefore likely not play a role in the mineralizing event. In the PLD, a limited number of the varitextured and pegmatitic rocks were analyzed and found to have geochemical trends and Pd/Pt ratios similar to mantle composition (Fig. 13), suggesting that such fluids did likely not play a role in redistributing or concentrating the PGEs. Fluid-induced flux-melting did however likely play a role in the formation of the cross-cutting leucogabbro and anorthosite zones (Fig 8D), observed in both the SRC and the PBC.

Lithotectonic Environment of the Swan River complex

In the area of the PLD and the Wollaston Domain, bordering to the west, the basement of the southern Hearne craton is dominated by circa 2.63 Ga migmatitic tonalite-granodiorite gneisses, containing minor enclaves of supracrustal rocks, and a much more widespread suite of 2580-2566 Ma hornblende-bearing granitoids (Lueaza River granitoid suite). Emplacement of the latter was closely followed by, or associated with, circa 2566 ± 3 Ma (Maxeiner et al. 2010) felsic volcanism. Associated pelite and partly pillowed mafic volcanic rocks suggest the presence of an ocean basin at this time. Deformed mafic volcanic xenoliths in 2562 Ma plutonic rocks of the SRC provide evidence for deformation prior to emplacement of the complex.

The trace element data for the SRC, with relatively low La/Lu_N ratios, but slightly elevated overall REE abundances and negative Nb and Zr anomalies (Fig. 11) could indicate: a) emplacement in a convergent plate tectonic setting, b) derivation from an enriched mantle

source in a non-convergent tectonic setting, and/or c) the effects of crustal contamination processes or a combination of these processes. An ϵNd of around +1.6 (Maxeiner et al. 2011) for the 2560 ± 1 Ma Wiley Bay Leucogabbro (sample RM0301-108) is considerably lower than the expected depleted mantle composition for that time (calculated ϵNd of +4.3 at 2560 Ma, Goldstein et al. 1984) and suggests input of evolved crustal material into the magma. Pd/Pt ratios (Fig. 13F) of the SRC are slightly higher than those for typical rift-related, mantle-derived magmas (Maier and Barnes 2004).

Many layered intrusions in the world, including the Bushveld Complex, the Munni Munni Intrusion, the Great Dyke, and the Stillwater Complex, display highly fractionated incompatible trace element patterns with negative HFSE anomalies (e.g., Hoatson and Sun 2002, Maier and Barnes 2004, Wilson and Chunnett 2006). Debate still exists in the literature about whether the crustal signature in these mafic magmas is due to crustal contamination during magma ascent or whether it reflects an enriched source in the sub-continental lithospheric mantle. However, there is general agreement that despite their arc-like trace element geochemistry, many of these intrusive complexes were emplaced within extensional, mid-continental rifts. Similarly, one could argue that given the extent, lithological make-up, petrography and the Pd/Pt ratios of the SRC, it could be interpreted to have been emplaced in an extensional environment, although examples of Archean anorthosite-leucogabbro complexes emplaced in intra-oceanic subduction zone settings also exist in the literature (e.g., Polat et al. 2010, 2011).

However, the apparent lack of post-2562 Ma supracrustal rocks within the PLD, or anywhere within the southern Hearne craton, could be used to argue against such a rifting model. A

dearth of Siderian (2.5-2.3Ga) supracrustal rocks in the PLD would suggest that emplacement of the SRC did not lead to the formation of a larger ocean or even a failed rift. Because of this and because of the Swan River complex's restricted presence to the PLD in relation to other parts of the southern Hearne craton, a mantle plume origin for the complex seems a more likely interpretation.

Monazite growth within a migmatitic pelite at circa 2549 Ma (Maxeiner et al. 2011) and 2529 Ma titanite in the PLD (Annesley et al. 1992), as well as 2566 $\pm$ 23/-21 Ma metamorphic zircon (ibid) in a 2689 Ma tonalitic gneiss from the neighbouring Wollaston Domain, are evidence for a syn- to post-Swan River complex high-grade regional metamorphic event. A suite of 2540 Ma megacrystic monzonite has geochemical similarities to magmas emplaced in modern arc environments (Maxeiner et al. 2011) and together with the previously documented 2566 Ma rhyolitic arc rocks (Maxeiner et al. 2010) suggest a prolonged subduction history for the rocks of the PLD. The emplacement of the SRC plutonic rocks has to be placed within this plate tectonic context.

The SRC may represent an example of plume-arc interaction, typical of other Neoarchean cratons such as the processes described for the Abitibi belt in the Superior province (Dostal and Mueller 1997, Wyman and Kerrich 2010). Based on the data presented in this paper and on previous work (Maxeiner et al. 2011), the southern Hearne craton may have been a continental margin at circa 2580 Ma (Fig. 16). The 2.58-2.57 Ga Lueza River granitoid suite, 2.566 Ga rhyolitic rocks and >2.562 Ga mafic volcanic rocks with associated pelites and iron formation are all consistent with the presence of an ocean basin and the development of a subduction zone under the southern Hearne craton (Fig. 16A). Emplacement of the 2.562-

2.560 Ga SRC in this context could best be explained by invoking extension above this subduction zone, which caused flooding of mafic magmas within the area of the PLD (Fig. 16B). This may have been achieved through interaction of a mantle plume with the subduction zone. Emplacement of a suite of 2.540 Ga megacrystic monzonite and quartz monzonite (Maxeiner et al. 2011) marks the end of subduction (Fig. 16C) and represents the final stage of Neoarchean igneous activity in the southern Hearne craton, followed by a period of quiescence in the PLD for the Siderian to Rhyacian Periods (Fig. 16D).

At 2075 Ma (Ansdell et al. 2000), extension in the Hearne craton was possibly focused on the zone of weakness previously developed along the SRC. A bimodal suite of mafic and felsic volcanic rocks with an overlying succession of quartz-rich sedimentary rocks has been interpreted as evidence for a rift-passive margin succession that was marking the eastern margin of the Hearne craton (Yeo and Delaney 2007). Ultimately, this rifting event (Fig. 16E) led to the formation of the Manikewan Ocean (Stauffer 1984).

Closure of this ocean began with intraoceanic subduction (e.g., Syme et al. 1998 and references therein). Based on the interpretation of the 1917-1913 Ma PBC as having been emplaced in a continental arc setting (Maxeiner and Rayner 2011), the ocean was also closing by way of subduction underneath the Hearne craton (Fig. 16F).

Mineral Deposit Models

Both the Swan River and Porter Bay mafic complexes are dominated by leucocratic to mesocratic gabbro-norite, but range from pyroxenite to diorite (Maxeiner et al. 2011). The textures associated with mineralization include varitextured, pegmatitic, brecciated, and, less

frequently, cumulate layering. Most of the mineral occurrences are low-sulfide with dissemination of copper-iron sulfides of generally <5%. Breccia zones are of particular interest as they appear to occur near some of the highest concentrations of PGEs, particularly in the eastern portion of the Love Lake pluton and in the Patterson Island pluton.

Layered mafic-ultramafic intrusions are one of the most important sources of economic concentrations of PGEs. Most authors (e.g. Eckstrand and Hulbert 2007, Zientek 2012) have subdivided these magmatic ore deposits into two types. 'Layered-stratiform-type' deposits (or 'reef'-type) are laterally continuous, narrow horizons that commonly extend over the entire width of the intrusion. Immiscible sulfide liquids have been incorporated at specific stratigraphic levels, generally marking a distinct lithological or petrological change. Cu-Ni-PGE bearing sulfides are generally disseminated. 'Contact-type' deposits, as the name implies, generally occur along the margins of mafic intrusions, either near the bottom or side of the plutons. They have a much smaller footprint, generally measuring 100s of metres in extent, and are commonly characterized by strongly variable grain sizes and accompanied by abundant heterogeneous breccia zone. Sulfides are also generally disseminated to net-textured.

Several areas of Ni-Cu-PGE mineralization in the PLD have been identified as being affiliated with the 2.562-2.560 Ga SRC magmas and with the 1.917-1.913 Ga PBC. On the basis of the current study, sulfide mineralization and associated enrichment of PGEs is interpreted to be of igneous origin. This is borne out by the disseminated, blebby to net-textured appearance of the sulfide minerals and their being intergrown with the original igneous silicate phases of the

intrusions, where preserved. In addition, sulfides in the SRC are deformed by the main regional fabric.

According to Eckstrand and Hulbert (2007), reef-type or stratiform magmatic nickel-copper-PGE deposits of large layered intrusions such as the Stillwater and Bushveld complexes, formed either as a result of mixing of a second pulse of magma above a mostly consolidated first magma pulse, or the PGEs are carried in rising residual fluids within one large fractionating pluton. Both the SRC and the PBC are each believed to be the product of a single magma pulse, based on the tightly constrained age relationships and the documented geochemical characteristics, which suggest that the rocks formed as a result of one fractional crystallization event. Therefore, similar to the single-pulse Skaergaard intrusion (Irvine et al. 1998, Andersen 2006), PGE mineralization in some of the PLD plutons may have resulted in the formation of reef-type mineralization due to continuing differentiation of an inwardly cooling and younging intrusion leading to enrichment of the magma in chalcophile elements and sulfur.

There is evidence for some remobilization of sulfides in shear zones and along late faults, possibly during either the 2550 Ma or later thermotectonic overprints. But such features represent a minor component. Metamorphism has also caused the silicate phases of the gabbroic rocks to recrystallize, resulting in widespread prograde amphibolitization as well as the formation of greenschist facies mineral assemblages. .

Irrespective of the age of the host rock, the PGE-(Cu-Ni) occurrences of the Neoarchean SRC and the Paleoproterozoic PBC share many textural and lithological characteristics (Fig. 8 and

Fig. 15) with each other and with those described from layered stratiform deposits in large layered intrusions such as Bushveld or Stillwater, but even more so to contact-type deposits such as the Coldwell Complex, and the chaotic Lac des Iles deposit (Hinchey et al. 2005) which preserves both contact-type and layered stratiform-type characteristics.

Sulfide minerals at Lac des Iles are disseminated and magmatic in origin, although zones of remobilization also exists. Layering is rarely preserved and, if so, is very subtle and discontinuous in nature. The 2.689 Ga (Stone et al. 2003) Mine Block Intrusion, host to one of the main ore bodies, is characterized by strongly heterogeneous gabbroic rocks, with varitextured and brecciated varieties. As a result, PGE concentrations are highly erratic (Hinchey et al. 2005). The bulk of the PGEs are thought to have been introduced by pulses of fertile primitive magmas, but in a much more energetic and dynamic environment than that proposed for the quiescent magma chambers of layered intrusions such as Stillwater or Bushveld (ibid).

Despite the textural and lithological similarities between the two Saskatchewan mafic complexes and those of the Lac des Iles intrusion, there is considerable difference in their geochemistry. The Pd/Pt ratios of the SRC (Fig. 13) are comparable to those of PGE-dominated deposits from around the world, such as the Bushveld Complex or the Great Dyke, and are also comparable to those of mantle-derived magmas (Maier and Barnes 2004). Pd/Pt ratios of the PBC appear slightly more elevated, but still much lower than those of the Lac des Iles intrusion. Despite these high Pd/Pt ratios at Lac des Iles, a sulfide liquid is still envisaged as having played a role in the formation of the deposit (Barnes and Gornwe 2011), albeit in a staged process, where the magma that fed the intrusion was likely derived from a secondary

magma chamber rather than being a primary mantle melt. It is possible that a similar process was at work for the magmas of the PBC, and such a two-staged emplacement mechanism was indeed invoked by Maxeiner and Rayner (2011). In that model, the PBC developed in a continental arc environment and its magmas were derived from a chamber at the base of the crust where fractionation processes were taking place.

In conclusion, the described mineral occurrences of the SRC are dominated by varitextured and brecciated host rocks and are therefore most consistent with having formed as contact-type PGE-(Cu-Ni) deposits as defined by Eckstrand and Hulbert (2007). The potential for a laterally continuous, narrow mineralized zone extending over the entire width of an intrusion (reef-type deposit) exists theoretically, on the basis of the size of some of the individual intrusions of the SRC, that the magma was likely mantle-derived, the fact that fractional crystallization processes have been documented, and that cumulate phases and inch-scale layering are present. The perceived predominance (possibly as a result of widespread glacial drift cover) of mafic over ultramafic components in the plutons of the SRC, however, represents a significant deviation from the large layered intrusions such as the Stillwater or Bushveld complexes.

The mineral occurrences of the PBC most resemble those of the Lac des Iles intrusion, in terms of the observed heterogeneous textures, smaller size of intrusions and similarity to contact-type PGE deposit models (e.g. Eckstrand and Hulbert 2007), although discrepancies exist in the literature about the origin of Lac des Iles type mineralization (e.g. Hinchey et al. 2005, Barnes and Gornall 2011).

Conclusions

The Peter Lake Domain represents a unique part of the southern Hearne craton that has preserved within it several distinct suites of predominantly mafic intrusions, spanning 700 million years of Earth history and representing one of the largest accumulations of such magmas in Canada. The Swan River complex represents the largest component of the mafic suites that make up the PLD. Two of its components, the Love Lake leucogabbro and the Swan Lake pegmatitic sulfide-bearing gabbro, provided U-Pb crystallization ages of 2562 ± 1 Ma and 2562 ± 3 Ma, respectively. The Wiley Bay gabbro crystallized at 2560 ± 3 Ma, which established the timing of emplacement of SRC magmas to between 2562-2560 Ma.

The previously described Paleoproterozoic Porter Bay complex and mafic component of the predominantly felsic Wathaman Batholith were emplaced between 1917-1912 Ma and 1859 and 1854 Ma, respectively (Maxeiner and Rayner 2011). A sample of sulfide-bearing leucogabbro of the PBC yielded a U-Pb crystallization age of 1913 ± 1 Ma. Igneous textures preserved within the SRC and PBC, including micro-rhythmic layering and trough cross-bedded layering, rival those seen in the Stillwater Complex and the Skaergaard Intrusion. Similar to those classic layered intrusions, the magmatic textures observed in the PLD mafic plutons are a result of a combination of primary magmatic processes during fractional crystallization and later post-nucleation processes affecting the crystal mush, which likely led to refinement of existing layering. Geochemical data of the SRC are consistent with the magmas having been derived from a mantle source during a single phase of plutonism and subsequent fractional crystallization. The crystal mush zones of the SRC were also affected

by fluid-induced flux-melting, locally resulting in cross-cutting, pegmatitic and varitextured leucogabbro and anorthosite zones.

On the basis of its age, geochemistry and relationship to other volcanic and plutonic rocks of the PLD, the SRC is interpreted to have been the product of plume-arc interaction. The complex is thought to have been emplaced in an extensional setting, as a result of a mantle plume interacting with a subduction zone that was developed underneath the southern Hearne craton. A well-established rifting event at 2075 Ma (Ansdell et al. 2000) broke the craton apart at approximately the same location where the SRC had previously been emplaced. Rifting ultimately led to the formation of the Manikewan Ocean (Stauffer 1984). Based on the interpretation of the 1917-1912 Ma PBC as having been emplaced in a continental arc setting (Maxeiner and Rayner 2011), the ocean began to close by way of subduction underneath the Hearne craton (ibid) as well as by intraoceanic subduction (Syme et al. 1998).

This study has shown that Ni-Cu-PGE mineralization hosted by both the SRC and PBC mafic intrusions of the PLD is of igneous origin. Therefore the ages of mineralizing events are constrained to 2562 ± 3 Ma, the crystallization age of the Swan Lake pluton and to 1913 ± 1 Ma, the crystallization age of the Patterson Island pluton. Textures associated with mineralization include varitextured, pegmatitic, brecciated, and, less frequently, cumulate layering. Most of the mineral occurrences are low-sulfide with dissemination of copper-iron sulfides of generally <5%. Breccia zones are of particular interest as they appear to occur near some of the highest concentrations of PGEs, particularly in the eastern portion of the Love Lake pluton and in the Patterson Island pluton. Mineral occurrences in the PLD are mostly

classified as Lac-des-Iles type, with similarities to Eckstrand and Hulbert's (2007) magmatic contact-type deposits and less so to the reef-type deposits.

Acknowledgements

The manuscript greatly benefitted from thorough peer reviews by Dr. M. Bickford and an anonymous reviewer, as well as earlier reviews by Dr. Ken Ashton and Dr. Ryan Morelli. We are grateful for the support and assistance of the staff of the Geochronology and Mineralogy Laboratories of the Geological Survey of Canada, with particular thanks to Raymond Chung, Ron Christie, Julie Peressini, Linda Cataldo and Carole Lafontaine. This is Natural Resources Canada's Earth Science Sector Contribution number 20160357.

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Table Titles

Table 1: Highlights of Cu-Ni-PGE mineral exploration history and results in the Peter lake domain of the southern Hearne craton

Table 2: U-Pb TIMS analytical data

Supplementary data Table S1: Wholerock geochemical results

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Figure Captions

Fig. 1: The Peter Lake Domain in the context of the Reindeer Zone (Trans-Hudson Orogen) of Saskatchewan and Manitoba; modified from Maxeiner and Rayner, 2011; abbreviations:

PLD – Peter Lake Domain, WD – Wollaston Domain, WB – Wathaman Batholith

Fig. 2: Geological map of the Love Lake pluton in the southwestern portion of the Peter Lake Domain.

Fig. 3: Field photos of the Love Lake pluton, Swan River complex: **A** – A rare outcrops with well-developed rhythmic layering within the main western part of the Love Lake pluton; **B** – inclusions within the Love Lake pluton up to 1 m in diameter within a leucocratic gabbro matrix.

Fig. 4: Photomicrographs and additional field photos of the Love Lake pluton, Swan River complex: **A** – Cross-polarized photograph of sample RM0501-017 from the Korvin Lake area; note variably amphibolitized clinopyroxene crystals (cpx) and sericitized plagioclase (pl); **B** – Outcrop photograph of a brecciated and mineralized gabbro; **C** – typical pyrrhotite (po) – chalcopyrite (cpy) association within a gabbroic rock from the Korvin Lake area; same field of view as image ‘a’; **D** – pyrrhotite (po) grain with enclosed subhedral pyrite (py) within sample RM0501-017 from the Korvin Lake area.

Fig. 5: Concordia plots for Swan River complex samples with inset images of representative zircon grains: A) Leucocratic gabbro of the Love Lake pluton; B) Swan Lake gabbro; C) Wiley Bay leucogabbro.

Fig. 6: Geological map of the Swan Lake and Patterson Island area.

Fig. 7: Field photos and photomicrographs of the Swan Lake pluton, Swan River complex: **A** – Typical example of varitextured gabbro from the margin of the central part of the Swan Lake pluton; note the ultramafic inclusions; **B** – Close-up of a mineralized gabbro from one of the trenches at SMDI 1896; **C** – Millimetre-sized, polymineralic sulfide blebs interstitial to plagioclase grains (~An70); pyrrhotite (po) and chalcopyrite (cpy) dominated over minor pentlandite (pn) in typical mineralized leucogabbro; sample RM0501-067; **D** – Blebbly pyrrhotite and chalcopyrite overgrown by subhedral pyrite (py); most likely in response to sulfur release from pyrrhotite during retrograde cooling.

Fig. 8: Field photographs of the Reindeer Lake intrusions related to the Swan River complex: **A** – micro- and macro-rhythmic layering; **B** – Pegmatitic zones of gabbro are commonly parallel to cumulate layering; possibly the result of flux-melting due to water infiltration along faults that formed during cooling of the magma chamber; note slight oblique nature of contact of pegmatitic zone (solid line) relative to cumulate layering (dashed line) **C** – Pegmatitic gabbro with clinopyroxene and coronitic orthopyroxene; **D** – Microrhythmic layering (Gal) cut by mafic dyke (md); note cross-cutting pegmatitic gabbro (p) at top of photo cutting the cumulate layering; mafic dyke postdates the pegmatitic zones.

Fig. 9: Harker-type variation diagrams of mafic intrusions of the Swan River complex and Porter Bay complex.

Fig. 10: Pearce element ratio plots for the Reindeer Lake, Swan Lake and Love Lake areas.

Fig. 11: Chondrite-normalized trace element diagrams of gabbros from the Reindeer Lake area, the Swan Lake and Love Lake plutons, and gabbros from the Warner Lake area. Blue field of PBC trace element patterns from Maxeiner and Rayner (2011)

Fig. 12: Sm/Y versus La/Sc diagram using wholerock geochemical data allows a broad distinction between rocks of the 2562 Ma Swan River complex and the younger 1917-1913 Ma Porter Bay complex.

Fig. 13: Chalcophile trace element ratios of mafic rocks of the Swan River complex and Porter Bay complex compared to mantle compositions and samples from other mafic intrusions; abbreviations: JM – JM reef, Stillwater Complex; M – Mantle; MR – Merensky reef; SuD – Sudbury Complex.

Fig. 14: Concordia plot of sample RM0401-036 from Patterson Island gabbro; inset: image of zircons.

Fig. 15: Field photographs of the micro-rhythmic layering in the Peter Lake Domain: **A** – doublets of alternating anorthositic and melagabbroic layers in the Patterson Island pluton of the Porter Bay complex; **B** – trough cross-bedded igneous layering in the Patterson Island pluton; younging to the top of the photo; **C** – trough cross-bedded igneous layering gabbroic rock of the Swan River complex.

Fig. 16: A series of schematic plate tectonic snapshots representing the simplified lithotectonic history of the southeast Hearne craton and Manikewan ocean from 2580 Ma to 1910 Ma. For further explanation see text.

Table 1

Location	Company	Year Reported	SMDI	Rock# or Drill Hole#	Sample type or width	Ni (wt%)	Cu (wt%)	Pt (ppb)	Pd (ppb)	Au (ppb)
Peter Lake East ('Korvin Lake')	SMDC	1982	1845	PL20-74	surface channel (1m)	0.02	0.6	15	62	190
				PL20-114	grab	1.3	0.33	2735	2685	70
				PL20-115	grab	0.23	0.43	3580	4275	200
Peter Lake East ('Korvin Lake')	Lacana Mining Corp	1985	1845	M-91	grab	0.03	0.21	359	336	na
Haglund East Lake	Lacana Mining Corp	1985		C-130	grab	na	0.41	88	498	na
Rutherford Lake	Lacana Mining Corp	1986		M74		0.02	0.39	233	222	na
Rutherford Lake	Canadian Platinum Corp.	2012		11574	grab	0.13	0.36	940 (PGE)		na
Patterson Island (Antoine showing)	Lacana Mining Corp	1985		T37(trench 4)	grab	0.02	1.482	298	3160	na
				T41 (trench 4)	grab	0.02	1.06	477	4340	na
				Trench 4	surface channel (5.5m)		0.66	242	2515	na
Swan Lake	SMDC	1982		PL20-150 (trench 7)	grab sample	0.12	0.33	na	na	na
				PL20-151 (trench 7)	grab sample	0.03	0.32	na	na	na
Swan Lake	Lacana	1985		?	grab sample	na	na	654	1920	na
Swan Lake	Canadian Platinum Corp.	2012		SW 08	71.6m	0.182	0.519	236	313	154
					incl. 5.0m	0.463	0.882	1212	953	551
				SW 19	25.6m	0.098	0.68	89	192	160
					incl. 5.0m	0.21	1.403	150	352	287

Note: na - 'not analyzed' and/or 'not available'

Table 2: U-Pb TIMS analytical data

Fract. ¹	Description ²	Wt. μg	U ppm	Pb ³ ppm	206Pb ⁴ 204Pb	Pb ⁵ pg	Isotopic Ratios ⁶						Ages (Ma) ⁸						% Disc		
							208Pb	207Pb	±1SE	206Pb	±1SE	Corr. ⁷	207Pb	±1SE	206Pb	±2SE	207Pb	±2SE		207Pb	±2SE
							206Pb	235U	Abs	238U	Abs	Coeff.	206Pb	Abs	238U		235U	206Pb			
RM0301-115 (z7880) Love Lake Leucogabbro (UTM coordiantes; Zone 13; E: 562975; N: 6339906]																					
Z1A (2)	Br, Clr, Eq, NM3	7.5	93	52	2056.2	10.4	0.17	11.474	0.014	0.48820	0.00044	0.9102	0.17045	0.00009	2562.9	3.8	2562.4	2.3	2562.1	1.8	-0.04
Z1B (2)	Br, Clr, El, NM3	7.1	93	53	2996.5	6.69	0.19	11.453	0.014	0.48724	0.00046	0.9162	0.17048	0.00009	2558.7	3.9	2560.8	2.2	2562.4	1.7	0.17
Z1D (1)	Br, Clr, El, NM3	6.8	98	57	828.5	25	0.21	11.483	0.020	0.48809	0.00078	0.8568	0.17062	0.00015	2562.4	6.7	2563.2	3.2	2563.8	3.0	0.06
RM0401-039 (z8487) Swan Lake gabbro (UTM coordiantes; Zone 13; E: 620058; N:6381579]																					
Z1A (1)	Co, Clr, An, M1	7.3	589	320	11991	10.1	0.23	10.372	0.013	0.45439	0.00045	0.9493	0.16555	0.00007	2414.7	4	2468.5	2.3	2513.2	1.4	4.69
Z1B (4)	Co, Clr, An, M1	6.8	172	89	1623.6	21.6	0.09	11.124	0.015	0.47753	0.00050	0.8898	0.16894	0.00011	2516.5	4.3	2533.5	2.5	2547.2	2.1	1.46
Z1C (10)	Co, Clr, An, M1	7	206	115	2259.6	19.3	0.17	11.296	0.014	0.48268	0.00048	0.8986	0.16973	0.0001	2538.9	4.1	2547.9	2.3	2555.0	1.9	0.76
RM0301-108 (z7879) Wiley Bay leucogabbro (UTM coordiantes; Zone 13; E: 639508; N: 6388594]																					
Z1A (2)	Br, Clr, An, DIA	5.7	123	71	6835.4	0.46	0.21	11.382	0.013	0.48517	0.00048	0.9100	0.17014	0.00009	2549.8	4.1	2554.9	2.2	2559.0	1.7	0.44
Z1B (2)	Br, Clr, An, DIA	6.5	83	46	5113.6	0.91	0.16	11.385	0.013	0.48481	0.00044	0.9366	0.17032	0.00007	2548.2	3.8	2555.2	2.2	2560.8	1.5	0.59
Z1C (2)	Br, Clr, An, DIA	6.1	106	60	849.4	23.5	0.19	11.451	0.018	0.48802	0.00047	0.7993	0.17017	0.00017	2562.1	4.1	2560.6	2.9	2559.3	3.2	-0.13
RM0401-036 (z8619) Patterson Island leucogabbro (UTM coordiantes; Zone 13; E: 636752; N: 6392093]																					
Z1A (1)	Co, Clr, An, NM0	4.7	151	56	1940.6	7.89	0.13	5.5696	0.008	0.34479	0.00035	0.8747	0.11716	0.00008	1909.6	3.4	1911.4	2.3	1913.3	2.5	0.22
Z1D (1)	Br, Clr, An, NM0	9.8	543	203	6482.2	17.7	0.14	5.5680	0.007	0.34472	0.00037	0.9186	0.11715	0.00006	1909.3	3.6	1911.2	2.2	1913.1	1.9	0.23
Z1F (1)	Br, Clr, An, NM0	6.5	234	86	8468	3.87	0.12	5.5666	0.007	0.34458	0.00033	0.9220	0.11717	0.00006	1908.7	3.1	1910.9	2	1913.4	1.7	0.29

Notes:

¹ Fraction name Number of grains making up each fraction shown in parentheses. All zircon fractions were mechanically abraded (Krogh, 1982).

² Zircon descriptions: An=Anhedral, Br=Brown, Co=Colorless, Clr=Clear, El=Elongate prism, Eq=Equant prism, DIA=Diamagnetic @1.8A -½°ss, NM0=NonMag @1.8A 0°SS, M1=Magnetic @ 1.8A 1°SS, NM3=NonMag @1.8A 3°SS.

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 (SE 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-Kramers (1975) compositions.

⁷ Correlation Coefficient

⁸ Corrected for blank and common Pb, errors quoted are 2 standard error (SE) in Ma

SampleName	RckName	LithUnit	GenArea	UTM-E	UTM-N
Reindeer Lake gabbro samples					
RM0301-108	leucogabbro	Reindeer Lk	Wiley Bay	639505	6388602
RM0401-065	gabbro	SGa	NW Fontaine Island	645224	6407805
RM0401-075	gabbro	SGn	NW of Fontaine Islan	648931	6407612
RM0401-076	leucogabbro	SGa	NW of Fontaine Islan	648972	6407868
RM0401-063	gabbro	SGa	SW Crane Island	649397	6408047
RM0401-034	gabbro	SGa	SW Crane Island	651677	6410460
RM0401-047	gabbro	SGa	S MacLean Bay	658392	6414063
RM0401-049	anorthosite	SGa	S MacLean Bay	659975	6414230
RM0401-096	gabbro	SGn	W Feaviour Peninsula	660081	6411828
RM0401-029	gabbro	SGa (2562)	McLean Bay	660128	6413076
RM0401-038	gabbro	SGa (2562)	McLean Bay	660128	6413076
Swan Lake pluton samples					
RM0501-058	leucogabbro	Swan Lake	NW Campbell	597742	6353292
RM0501-056	gabbro	SGa	NW Campbell	598182	6352575
RM0501-053	leucogabbro	SLg	Campbell to Rutherfo	599915	6354493
RM0401-043	gabbro	SLgb (2562)	Swan Lake	620058	6381579
RM0401-041	gabbro	SLgb (2562)	Swan Lake	620058	6381579
RM0501-063	leucogabbro	SLgb (2562)	Swan Lake Trenches	620054	6381744
Love Lake pluton Samples					
RM0201-127	leucogabbro	Love Lake	S of Ziggy Lake	561399	6339955
RM0201-029	leucogabbro	SLg (2562)	Road-Peter Lake	562952	6340090
RM0201-115	leucogabbro	SLg	S Peter Lake	563442	6339653
RH0201-551	leucogabbro	SA n	SE of Peter Lake	565533	6340398
RM0501-016	gabbro	SGa	Peter Lake East	575705	6339079
RM0201-168	peridotite	SUp	SE Peter Lake	567367	6340331
RM0501-015	pyroxenite	SUp	Peter Lake East	575151	6337947
RM0501-029	monzodiorite	SGa	Peter Lake East	573179	6337052
Warner Lake gabbro samples					
RM0201-049	gabbro	Warner	SW Warner Lake	562629	6329633
RM0201-026	leucodiorite	SDi	Warner Lake	563834	6334568
RM0201-036	pyroxenite	SUp	Warner Lake	564215	6335237
RM0201-024	gabbro	SGa	Warner Lake	564307	6334570
RM0201-039	gabbro	SDi	Love Lake area	565899	6336280
RM0201-013	gabbro	SGa	Gravel Pit	571800	6332570
RM0201-014	diorite (to gabbro	SDi	Gravel Pit	572460	6333248
RM0201-046	pyroxenite	SUp	Wathaman River	576340	6329378

SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O
49.27	1.033	17.3	11.47	0.177	5.55	9.86	3.1	0.59
49.31	1.163	16.24	12.77	0.18	6.85	8.29	2.74	0.74
52.22	0.458	15.83	8.87	0.148	9.33	9.03	2.32	0.58
48.77	0.39	21.32	7.26	0.11	7.04	9.07	2.75	1.15
47.58	0.26	19.72	8.7	0.12	9.69	8.96	2.36	0.38
45.83	1.27	16.72	10.42	0.12	8.73	10.58	2.47	1.31
50.98	0.27	17.72	6.97	0.13	8.57	11.16	2.38	0.37
48.94	0.23	28.69	3.38	0.04	1.04	13.17	3.23	0.29
47.12	0.27	18.19	7.55	0.12	12	10.91	1.41	0.52
47.39	0.158	21.41	7.01	0.109	8.32	10.79	2.01	0.72
42.45	2.774	13.82	18.15	0.21	7.75	9.61	1.58	0.38
52.08	1.133	18.32	10	0.168	3.55	8.28	3.92	1.09
51.19	0.699	14.34	10.65	0.218	7.46	8.68	3.29	1.75
49.43	2.219	17.63	12.58	0.217	3.36	7.39	3.96	1.2
48.5	0.67	15.9	11.27	0.2	8.18	11.33	2.08	0.41
44.28	0.15	11.62	11.75	0.2	16.25	10.4	1.04	0.24
49.29	0.94	20.51	10.48	0.14	3.41	9.28	3.49	1.04
45.51	1.005	18.39	11.64	0.146	5.63	14.42	1.51	0.41
48.07	1.127	18.37	12.79	0.178	4.8	9.78	2.87	0.52
48.87	1.098	18.08	12.71	0.178	4.72	9.36	3.04	0.83
47.22	1.51	16.01	15.76	0.23	5.46	8.84	2.67	0.81
48.06	0.24	21.55	6.48	0.11	6.11	12.77	1.96	0.93
42.51	0.27	5.9	13.41	0.15	27.52	3.48	0.39	0.12
47.5	0.54	9.94	11.07	0.27	15.38	9.27	1.4	1.84
56.45	1.04	17.46	9.33	0.19	2.13	5.15	4.7	1.96
40.58	0.317	14.33	14.45	0.183	15.38	7.8	0.62	0.97
55.16	0.644	16.24	7.59	0.196	3.81	5.77	3.35	3.63
49.3	0.35	5.85	10.43	0.18	17.72	12.41	0.61	0.41
51.49	0.772	15.36	9.1	0.159	4.78	7.65	2.64	3.6
49.25	1.13	17.71	11.12	0.18	5.82	9.14	3.3	1.31
50.37	1.24	18.01	12.53	0.19	3.76	8.1	3.28	0.92
56.36	0.54	14.45	8.56	0.18	6.77	7.44	3.46	1.41
44.12	0.34	14.56	11.7	0.17	13.45	9.97	0.92	2.19

P2O5	L.o.i	Total	Cr	Ni	Co	Sc	V	Cu
0.5	1.01	99.86	115	62	37	28	245	72
0.26	1.28	99.83	142	84	45	30	251	45
0.11	0.48	99.37	345	110	48	28	107	71
0.14	2.33	100.3	182	188	44	10	65	48
0.08	1.98	99.82	181	182	55	9	43	28
0.27	1.85	99.57	75	203	53	39	249	157
0.03	1.4	99.97	220	119	39	30	111	89
0.02	0.88	99.88	41	-20	12	8	93	106
0.06	2.14	100.3	566	295	61	22	98	39
0.02	2.13	100	60	416	54	15	63	23
0.1	2.22	99.06	53	186	112	58	1150	533
0.55	0.9	99.99	-20	-20	17	24	175	30
0.21	1.28	99.76	230	70	32	36	194	80
0.92	0.82	99.73	-20	-20	14	22	52	20
0.07	1.26	99.87	263	89	53	41	255	96
0.03	3.08	99.05	80	219	66	31	95	152
0.34	-0.01	99.43	-20	-20	25	14	176	20
0.11	1.44	100.2	-20	10	36	47	379	113
0.48	1.11	100.1	-20	36	35	23	290	50
0.46	0.73	100	-20	4	30	25	294	48
0.56	0.93	99.99	24	4	38	31	346	49
0.07	1.62	99.91	110	40	28	26	82	70
0.07	6.44	100.2	1770	612	116	18	88	24
0.16	2.16	99.53	750	250	33	39	122	20
0.46	1.05	99.93	-20	-20	9	18	68	20
0.06	4.55	99.23	27	292	91	9	79	211
0.2	3.45	100	65	36	24	22	143	83
0.05	2.57	99.88	1910	246	74	70	173	195
0.31	3.73	99.59	87	54	33	26	186	76
0.27	1.08	100.3	52	27	38	39	312	48
0.45	0.77	99.63	93	56	39	27	245	74
0.26	0.92	100.3	396	122	31	26	129	29
0.07	2.57	100	215	169	74	26	111	87

Pb	Zn	Bi	Cd	Sn	Sb	Pd	Ag	Pt
10	106	0	0	-1	0.3	0	-0.5	0
5	107	1	0	-1	-0.2	-4	-0.5	-5
-5	64	0	0	-1	-0.2	-4	-0.5	-5
6	54	0	0	-1	-0.2	-4	-0.5	-5
6	62	1	0	-1	-0.2	-4	-0.5	-5
-5	87	0	0	-1	-0.2	0	-0.5	0
-5	41	0	0	-1	-0.2	-4	-0.5	-5
7	-30	1	0	-1	-0.2	-4	-0.5	-5
5	58	0	0	-1	-0.2	5	-0.5	-5
-5	55	0	0	-1	-0.2	-4	-0.5	-5
-5	88	1	0	-1	-0.2	-4	-0.5	-5
-5	80	0	0	-1	1.3	-4	-0.5	-5
9	100	0	0	-1	2	-4	-0.5	-5
-5	110	0	0	-1	1.3	-4	-0.5	-5
-5	101	0	0	-1	-0.2	-4	-0.5	-5
-5	51	4	0	-1	0.3	20	-0.5	10
-5	70	0	0	-1	1.1	0	-0.5	0
6	72	0	-0.3	-1	0.2	4	-0.3	-5
-5	98	0	0	-1	-0.2	-4	-0.5	-5
6	105	0	-0.3	-1	-0.2	-4	-0.3	-5
18	140	-2	0.9	-1	-0.2	-2	1.7	-5
-5	40	0	0	-1	1.1	-4	-0.5	-5
-3	70	9	-0.3	-1	0.3	-2	-0.3	-5
-5	180	0	0	-1	1.3	-4	-0.5	-5
5	110	0	0	-1	1.3	0	-0.5	0
-5	106	0	0	-1	-0.2	-4	-0.5	-5
46	174	0	0	4	-0.2	-4	-0.5	-5
-5	82	0	0	22	-0.2	46	0.6	66
24	104	0	0	1	0.2	-4	-0.5	-5
27	100	2	0.5	-1	-0.2	-2	-0.3	-5
13	135	0	0	9	-0.2	-4	-0.5	-5
11	130	0	-0.3	-1	-0.2	-2	0.5	-5
-5	91	0	0	8	0.3	-4	-0.5	-5

Au	Rb	Cs	Ba	Sr	Tl	Ga	Ge	Ta	
	0	9	0	471	748	0.06	19	1.5	0.2
	5	14	0	553	606	0.13	19	1.5	0.1
	7	10	0	352	757	0.06	15	1.3	0.1
	7	28	0	414	750	0.26	15	0.7	0.1
	8	7	0	142	528	0.06	12	0.8	0
	0	21	0	599	892	0.16	20	1.2	0.2
	8	10	0	182	490	0.11	14	1	0
	4	3	0	168	1090	-0.05	21	0.9	0
	5	17	0	189	465	0.17	12	1.1	0
	5	22	0	330	514	0.19	15	1	0
	14	11	0	209	251	0.11	25	1.4	0.1
	-2	25	2	916	938	0.15	20	1.2	0.2
	-2	92	42	926	412	0.44	14	1.3	0.2
	-2	28	2	1151	1304	0.25	18	1.1	0.4
	10	10	1	151	609	0.07	17	1.1	0
	13	4	0	46	70	-0.05	9	1	0
	0	42	5	331	896	0.24	19	0.9	0.2
	4	19	0	158	735	0.14	17	1.3	0.1
	-2	11	0	450	943	0.09	23	1.3	0.1
	12	24	1	594	1000	0.15	21	1.1	0.1
	-2	22	1	486	766	0.14	22	1.6	0.2
	-2	25	1	492	766	0.18	15	0.9	0.2
	-2	1	0	28	51	-0.05	7	1.2	0
	-2	67	3	537	348	0.69	12	1.5	0.2
	0	34	1	1535	761	0.2	21	1.3	0.5
	-2	31	0	256	145	0.29	12	0.9	0.1
	2	128	3	1420	413	0.95	20	0.9	0.5
	12	7	0	148	79	0.12	8	1.6	0.1
	-2	158	5	1020	505	0.79	19	1.5	0.4
	-2	39	0	433	539	0.18	20	1.2	0.3
	-2	23	1	505	927	0.18	24	1.7	0.4
	-2	46	0	674	629	0.23	19	1.9	0.2
	-2	92	2	269	251	0.66	13	1.2	0.1

Nb	Hf	Zr	Y	Th	U	La	Ce	Pr
4.9	1	42	16	0.4	0.1	26.5	55	7.02
2	0	31	13	0.3	0.1	13.1	28	3.69
2.5	0	34	8	0.8	0.2	11.3	24	3.16
2.6	1	49	6	0.7	0.3	10.8	23	2.98
1	0	11	4	0.3	0.1	5.4	11	1.39
3.8	2	58	19	0.6	0.3	18.9	52	7.88
0.9	0	10	6	0.1	0.1	3.3	7	1.07
0.7	0	9	2	0.2	0.3	5.8	10	1.24
0.9	0	23	6	0.6	0.2	8	17	2.14
0.5	0	6	4	0.1	0	3.5	6	0.87
3.7	1	23	18	0.4	0.4	5.2	15	2.47
3.7	1	19	21	1.7	0.5	30.4	65	8.52
3.7	1	27	21	0.9	0.3	18.7	42	5.53
5.4	1	19	21	0.8	0.3	32.5	72	9.3
1.1	0	16	11	0.2	0.1	6.6	16	2.39
0.7	0	7	4	0.3	0.1	3	6	0.83
2.4	1	23	12	0.8	0.4	14.3	31	4.08
2.1	0	22	9	0.4	0.1	7.1	15	2.22
2	0	23	13	1	0.3	16.3	35	4.62
4.3	1	60	14	1.1	0.3	17.9	38	5.28
3.7	1	46	20	1.6	0.5	22.2	47	6.56
2.5	1	35	10	3.4	1.1	13.6	29	3.54
1.8	0	18	4	0.6	0.2	5.1	9	1.24
3.1	1	35	16	1.2	0.6	17.4	42	5.34
7.9	2	80	25	1.5	0.5	41.6	86	10.9
1.2	0	22	3	0.7	0.1	5.6	11	1.38
7.8	2	104	20	6	1.1	30.7	63	7.38
1.2	0	20	9	0.6	0.3	6.7	14	1.87
4.1	1	42	16	3.1	1.9	19.3	41	5.1
5.2	1	36	24	0.3	0.1	14.2	33	4.78
6.7	3	122	19	1.3	0.4	31.6	68	8.56
3.8	2	93	18	3.4	1	20.1	45	5.4
1.2	0	22	6	0.8	0.3	5.4	11	1.53

Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm
29	6	2	4.7	0.6	3.47	0.65	1.82	0.25
15	3.1	1.4	2.84	0.4	2.35	0.45	1.27	0.18
12	2.4	0.9	2.02	0.3	1.52	0.28	0.8	0.114
11	2.1	0.9	1.67	0.2	1.2	0.22	0.61	0.085
5	1	0.6	0.89	0.1	0.7	0.13	0.36	0.054
37	8	2.6	6.66	0.9	4.17	0.67	1.73	0.22
4	1.1	0.6	1.1	0.2	1.15	0.24	0.71	0.104
4	0.8	0.8	0.62	0.1	0.47	0.09	0.25	0.034
8	1.9	0.7	1.66	0.2	1.23	0.23	0.66	0.096
3	0.8	0.6	0.71	0.1	0.73	0.14	0.39	0.056
12	3.2	0.9	3.16	0.6	3.29	0.65	1.88	0.27
33	6.4	2.4	5.5	0.7	3.67	0.7	1.9	0.256
22	4.6	1.4	4.2	0.6	3.42	0.68	1.96	0.284
38	7.4	3.5	6.12	0.8	3.74	0.7	1.85	0.243
10	2.6	1	2.45	0.4	2.15	0.42	1.2	0.171
3	0.9	0.5	0.79	0.1	0.79	0.15	0.43	0.058
17	3.3	1.4	2.82	0.4	2.01	0.39	1.07	0.151
10	2.4	1	2.1	0.4	1.93	0.37	1.03	0.138
20	4	1.7	3.55	0.4	2.55	0.47	1.29	0.165
23	4.4	1.8	3.79	0.6	2.84	0.53	1.46	0.213
29	5.6	1.9	4.67	0.7	3.52	0.69	1.89	0.271
14	2.7	0.9	2.27	0.3	1.59	0.31	0.88	0.127
5	1	0.4	0.89	0.1	0.71	0.15	0.39	0.057
21	4	1.5	3.47	0.5	2.53	0.5	1.41	0.2
42	7.6	3.1	6.39	0.8	4.15	0.81	2.27	0.323
5	1.1	0.5	0.83	0.1	0.69	0.13	0.35	0.051
29	5.4	1.5	4.48	0.6	3.61	0.69	1.92	0.289
8	2	0.7	1.91	0.3	1.71	0.34	0.93	0.123
22	4.4	1.6	3.82	0.5	2.96	0.58	1.63	0.236
21	4.8	1.4	4.44	0.7	4.06	0.84	2.33	0.35
37	6.7	2.6	5.81	0.7	3.79	0.69	1.87	0.247
22	4.4	1.4	3.73	0.6	3.16	0.64	1.78	0.267
6	1.5	0.6	1.36	0.2	1.24	0.24	0.63	0.086

Yb	Lu
1.5	0.24
1.1	0.19
0.7	0.11
0.6	0.09
0.4	0.06
1.4	0.21
0.7	0.11
0.2	0.03
0.6	0.1
0.4	0.06
1.7	0.25
1.6	0.23
1.8	0.27
1.5	0.21
1	0.16
0.3	0.05
1	0.15
0.9	0.14
1.1	0.16
1.3	0.19
1.6	0.22
0.8	0.12
0.4	0.05
1.3	0.19
2.1	0.31
0.3	0.06
2	0.3
0.8	0.12
1.5	0.22
2.1	0.29
1.7	0.24
1.7	0.24
0.6	0.08

Draft

Table 2 - Wholerock geochemical analyses, Swan River Complex

SampleName RckName UTM-E UTM-N	Reindeer Lake gabbro samples											Swan Lake pluton samples						Love Lake pluton Samples							Warner Lake gabbro samples								
	RM0301-108 leucogabbro	RM0401-065 gabbronorite	RM0401-075 gabbronorite	RM0401-076 leucogabbro	RM0401-063 gabbronorite	RM0401-034 gabbro	RM0401-047 gabbro	RM0401-049 anorthosite	RM0401-096 gabbronorite	RM0401-029 gabbronorite	RM0401-038 gabbronorite	RM0501-058 leucogabbro	RM0501-056 gabbro	RM0501-053 leucogabbro	RM0401-043 gabbro	RM0401-041 gabbro	RM0501-063 leucogabbro	RM0201-127 leucogabbro	RM0201-029 leucogabbro	RM0201-115 leucogabbro	RM0201-551 leucogabbro	RM0501-016 gabbro	RM0201-168 peridotite	RM0501-015 pyroxenite	RM0501-029 monzodiorite	RM0201-049 gabbro	RM0201-026 leucodiorite	RM0201-036 pyroxenite	RM0201-024 gabbro	RM0201-039 gabbro	RM0201-013 gabbro	RM0201-014 diorite (to gab pyroxenite	RM0201-046 gabbro
	639505 6388602	645224 6407805	648931 6407612	648972 6407868	649397 6408047	651677 6410460	658392 6414063	659975 6414230	660081 6411828	660128 6413076	660128 6413076	597742 6353292	598182 6352575	599915 6354493	620058 6381579	620058 6381579	620054 6381744	561399 6339955	562952 6340090	563442 6339653	565533 6340398	575705 6339079	567367 6340331	575151 6337947	573179 6337052	562629 6329633	563834 6334568	564215 6335237	564307 6334570	565899 6336280	571800 6332570	572460 6333248	576340 6329378
(major elements in wt%)																																	
SiO2	49.27	49.31	52.22	48.77	47.58	45.83	50.98	48.94	47.12	47.39	42.45	52.08	51.19	49.43	48.5	44.28	49.29	45.51	48.07	48.87	47.22	48.06	42.51	47.5	56.45	40.58	55.16	49.3	51.49	49.25	50.37	56.36	44.12
TiO2	1.033	1.163	0.458	0.39	0.26	1.27	0.27	0.23	0.27	0.158	2.774	1.133	0.699	2.219	0.67	0.15	0.94	1.005	1.127	1.098	1.51	0.24	0.27	0.54	1.04	0.317	0.644	0.35	0.772	1.13	1.24	0.54	0.34
Al2O3	17.3	16.24	15.83	21.32	19.72	16.72	17.72	28.69	18.19	21.41	13.82	18.32	14.34	17.63	15.9	11.62	20.51	18.39	18.37	18.08	16.01	21.55	5.9	9.94	17.46	14.33	16.24	5.85	15.36	17.71	18.01	14.45	14.56
Fe2O3	11.47	12.77	8.87	7.26	8.7	10.42	6.97	3.38	7.55	7.01	18.15	10	10.65	12.58	11.27	11.75	10.48	11.64	12.79	12.71	15.76	6.48	13.41	11.07	9.33	14.45	7.59	10.43	9.1	11.12	12.53	8.56	11.7
MnO	0.177	0.18	0.148	0.11	0.12	0.12	0.13	0.04	0.12	0.109	0.21	0.168	0.218	0.217	0.2	0.2	0.14	0.146	0.178	0.178	0.23	0.11	0.15	0.27	0.19	0.183	0.196	0.18	0.159	0.18	0.19	0.18	0.17
MgO	5.55	6.85	9.33	7.04	9.69	8.73	8.57	1.04	12	8.32	7.75	3.55	7.46	3.36	8.18	16.25	3.41	5.63	4.8	4.72	5.46	6.11	27.52	15.38	2.13	15.38	3.81	17.72	4.78	5.82	3.76	6.77	13.45
CaO	9.86	8.29	9.03	9.07	8.96	10.58	11.16	13.17	10.91	10.79	9.61	8.28	8.68	7.39	11.33	10.4	9.28	14.42	9.78	9.36	8.84	12.77	3.48	9.27	5.15	7.8	5.77	12.41	7.65	9.14	8.1	7.44	9.97
Na2O	3.1	2.74	2.32	2.75	2.36	2.47	2.38	3.23	1.41	2.01	1.58	3.92	3.29	3.96	2.08	1.04	3.49	1.51	2.87	3.04	2.67	1.96	0.39	1.4	4.7	0.62	3.35	0.61	2.64	3.3	3.28	3.46	0.92
K2O	0.59	0.74	0.58	1.15	0.38	1.31	0.37	0.29	0.52	0.72	0.38	1.09	1.75	1.2	0.41	0.24	1.04	0.41	0.52	0.83	0.81	0.93	0.12	1.84	1.96	0.97	3.63	0.41	3.6	1.31	0.92	1.41	2.19
P2O5	0.5	0.26	0.11	0.14	0.08	0.27	0.03	0.02	0.06	0.02	0.1	0.55	0.21	0.92	0.07	0.03	0.34	0.11	0.48	0.46	0.56	0.07	0.07	0.16	0.46	0.06	0.2	0.05	0.31	0.27	0.45	0.26	0.07
Lo.i	1.01	1.28	0.48	2.33	1.98	1.85	1.4	0.88	2.14	2.13	2.22	0.9	1.28	0.82	1.26	3.08	-0.01	1.44	1.11	0.73	0.93	1.62	6.44	2.16	1.05	4.55	3.45	2.57	3.73	1.08	0.77	0.92	2.57
S																																	
Total	99.86	99.83	99.37	100.3	99.82	99.57	99.97	99.88	100.3	100	99.06	99.99	99.76	99.73	99.87	99.05	99.43	100.2	100.1	100	99.99	99.91	100.2	99.53	99.93	99.23	100	99.88	99.59	100.3	99.63	100.3	100
(selected trace elements; in ppm)																																	
Cr	115	142	345	182	181	75	220	41	566	60	53	-20	230	-20	263	80	-20	-20	-20	-20	24	110	1770	750	-20	27	65	1910	87	52	93	396	215
Ni	62	84	110	188	182	203	119	-20	295	416	186	-20	70	-20	89	219	-20	10	36	4	4	40	612	250	-20	292	36	246	54	27	56	122	169
Co	37	45	48	44	55	53	39	12	61	54	112	17	32	14	53	66	25	36	35	30	38	28	116	33	9	91	24	74	33	38	39	31	74
Sc	28	30	28	10	9	39	30	8	22	15	58	24	36	22	41	31	14	47	23	25	31	26	18	39	18	9	22	70	26	39	27	26	26
V	245	251	107	65	43	249	111	93	98	63	1150	175	194	52	255	95	176	379	290	294	346	82	88	122	68	79	143	173	186	312	245	129	111
Cu	72	45	71	48	28	157	89	106	39	23	533	30	80	20	96	152	20	113	50	48	49	70	24	20	20	211	83	195	76	48	74	29	87
Pb	10	5	-5	6	6	-5	-5	7	5	-5	-5	-5	9	-5	-5	-5	-5	6	-5	6	18	-5	-3	-5	5	-5	46	-5	24	27	13	11	-5
Zn	106	107	64	54	62	87	41	-30	58	55	88	80	100	110	101	51	70	72	98	105	140	40	70	180	110	106	174	82	104	100	135	130	91
Rb	9	14	10	28	7	21	10	3	17	22	11	25	92	28	10	4	42	19	11	24	22	25	1	67	34	31	128	7	158	39	23	46	92
Ba	471	553	352	414	142	599	182	168	189	330	209	916	926	1151	151	46	331	158	450	594	486	492	28	537	1535	256	1420	148	1020	433	505	674	269
Sr	748	606	757	750	528	892	490	1090	465	514	251	938	412	1304	609	70	896	735	943	1000	766	766	51	348	761	145	413	79	505	539	927	629	251
Tl	0.06	0.13	0.06	0.26	0.06	0.16	0.11	-0.05	0.17	0.19	0.11	0.15	0.44	0.25	0.07	-0.05	0.24	0.14	0.09	0.15	0.14	0.18	-0.05	0.69	0.2	0.29	0.95	0.12	0.79	0.18	0.18	0.23	0.66
Ga	19	19	15	15	12	20	14	21	12	15	25	20	14	18	17	9	19	17	23	21	22	15	7	12	21	12	20	8	19	20	24	19	13
Ge	1.5	1.5	1.3	0.7	0.8	1.2	1	0.9	1.1	1	1.4	1.2	1.3	1.1	1.1	1	0.9	1.3	1.3	1.1	1.6	0.9	1.2	1.5	1.3	0.9	0.9	1.6	1.5	1.2	1.7	1.9	1.2
Ta	0.2	0.1	0.1	0.1	0	0.2	0	0	0	0	0.1	0.2	0.2	0.4	0	0	0.2	0.1	0.1	0.1	0.2	0.2	0	0.2	0.5	0.1	0.5	0.1	0.4	0.3	0.4	0.2	0.1
Nb	4.9	2	2.5	2.6	1	3.8	0.9	0.7	0.9	0.5	3.7	3.7	3.7	5.4	1.1	0.7	2.4	2.1	2	4.3	3.7	2.5	1.8	3.1	7.9	1.2	7.8	1.2	4.1	5.2	6.7	3.8	1.2
Zr	42	31	34	49	11	58	10	9	23	6	23	19	27	19	16	7	23	22	23	60	46	35	18	35	80	22	104	20	42	36	122	93	22
Y	16	13	8	6	4	19	6	2	6	4	18	21	21	21	11	4	12	9	13	14	20	10	4	16	25	3	20	9	16	24	19	18	6
Th	0.4	0.3	0.8	0.7	0.3	0.6	0.1	0.2	0.6	0.1	0.4	1.7	0.9	0.8	0.2	0.3	0.8	0.4	1	1.1	1.6	3.4	0.6	1.2	1.5	0.7	6	0.6	3.1	0.3	1.3	3.4	0.8
(REEs in ppm)																																	
La	26.5	13.1	11.3	10.8	5.4	18.9	3.3	5.8	8	3.5	5.2	30.4	18.7	32.5	6.6	3	14.3	7.1	16.3	17.9	22.2	13.6	5.1	17.4	41.6	5.6	30.7	6.7	19.3	14.2	31.6	20.1	5.