GS2018-1

Re-examination of drillcore from southern Phillips Lake, and the possibility of a new nickel-mineralization–hosting sequence in the Thompson nickel belt, central Manitoba (part of NTS 63O1)

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In Brief:

- A mineralized ultramafic intrusion at southern Phillips Lake is hosted by a suite of metasedimentary rocks that appear to be distinct from the Ospwagan Group
- Metasedimentary rocks may have affinity with the Paleoproterozoic Paint sequence
- Ultramafic bodies hosted in Paint sequence rocks could be a viable exploration target for Ni-Cu deposits in the eastern Thompson nickel belt

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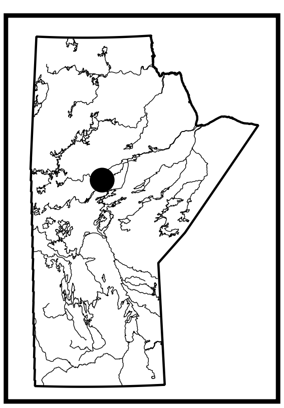

Summary

A mineralized ultramafic intrusion at southern Phillips Lake, along the eastern Thompson nickel belt (TNB), is hosted by a suite of granulite-facies gneisses that have been variously interpreted as Archean orthogneiss, Proterozoic Ospwagan group rocks and, most recently, Proterozoic Paint sequence rocks. A simplified stratigraphy, from the structural hangingwall to the footwall, in the vicinity of the ultramafic body consists of the following: biotite-hornblende gneiss, interpreted as part of the Archean basement; multicomponent gneiss, consisting of a variety of gneissic phases typically interlayered on a scale <10 m and likely representing tectonically interleaved Archean and Proterozoic phases; metawacke, consisting of interlayered biotite-garnet and biotite-orthopyroxene gneisses with local layers of diffusely banded silicate-facies iron formation; calcsilicate and impure marble; peridotite with increasing sulphide content toward the structural footwall contact; additional metawacke; mafic gneiss, likely representing either an Archean layered mafic complex or volcanic suite; and a succession of disrupted metawacke with local layers of well-banded silicate-facies iron formation. All of the previously listed phases are intruded by granitic pegmatite and, with the exception of the peridotite, metadiabase dikes.

Normalized, multi-element profiles of the metawacke suggest an affinity to Paint sequence rocks. The geochemical affinity of the calcsilicate and impure marble remains unconstrained. Current models for the generation of Ni-Cu deposits in the TNB call for the intrusion of ultramafic magmas into sulphidic Ospwagan group rocks, leading to sulphur saturation of the magma and the precipitation and concentration of Ni-Cu sulphides. Preliminary results suggest the mineralized peridotite at southern Phillips Lake is hosted by Paint sequence rocks. This implies ultramafic intrusions in Paint sequence rocks could be viable exploration targets in the TNB; however, the calcareous rocks of unknown affinity could also indicate the presence of Ospwagan group rocks at southern Phillips Lake. Additional work is required to constrain the affinity of the calcareous rocks.

Introduction

Phillips Lake is located 60 km south-southwest of Thompson in the eastern TNB (Figure GS2018-1-1). Inco Ltd. (now Vale Canada Ltd.) conducted airborne and ground geophysical surveys, diamond-drilling and outcrop mapping in the southern Phillips Lake area from 1952 to 1975 (Assessment File 92118, Manitoba Growth, Enterprise and Trade, Winnipeg). Their work led to the discovery of one large, and several smaller, ultramafic bodies in the area. Drillcore logging and mapping also resulted in the recognition of metasedimentary rocks, including 'skarn' and iron formation, that were restricted to narrow bands in the enclosing gneiss. Later work by Falconbridge Ltd. (now Glencore plc) from 1980 to 1996 (Assessment Files 94497, 94506) delineated an ultramafic body with >1800 m strike length and significant Ni-mineralization along the footwall contact (Figure GS2018-1-2). Falconbridge geologists interpreted the ultramafic body to be hosted in Archean gneiss; however, regional compilation mapping by the Manitoba Geological Survey (MGS) suggested that the mineralized ultramafic body was hosted by a 'ghost succession' of the Ospwagan group (Figure GS2018-1-3; Macek et al., 2006; McGregor et al., 2006; Zwanzig et al., 2007). To date, all Ni deposits identified in the TNB have consisted of ultramafic

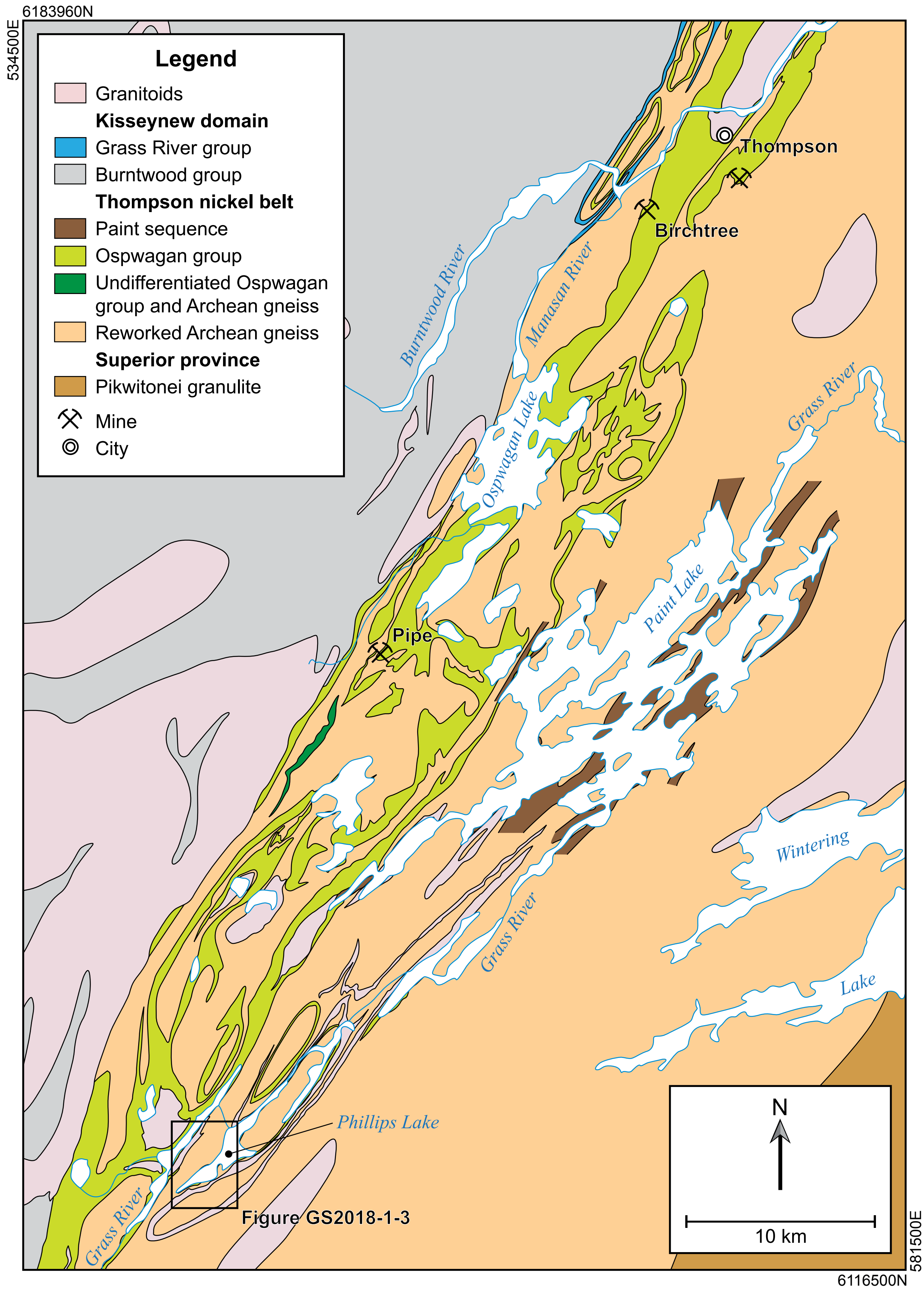

Figure GS2018-1-1: *Simplified geology of the central Thompson nickel belt (modified from Macek et al., 2006).*

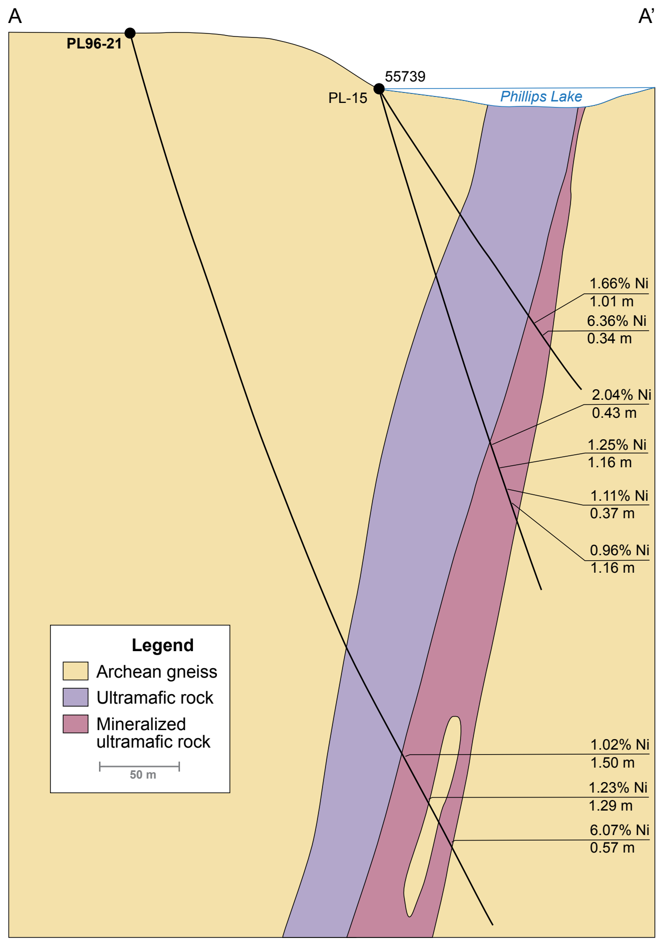

Figure GS2018-1-2: *Cross-section A–A', looking north through Falconbridge Ltd. drillholes PL-15 and PL96-21, and Inco Ltd. drillhole 55739 (modified from Assessment File 94497). The locations of drillholes and section A–A' are shown in Figure GS2018-1-3.*

bodies spatially associated with Ospwagan group rocks (Bleeker, 1990; Macek et al., 2006; Zwanzig et al., 2007).

Most recently, shoreline mapping by the MGS in 2012 suggested the presence of a newly recognized metasedimentary sequence, informally termed the 'Paint sequence', on the central islands and point, and along the west shore, of southern Phillips Lake (Figure GS2018-1-3; Couëslan, 2012, 2016). This suggests that Paint sequence rocks, rather than a ghost succession of Ospwagan group rocks, may host the mineralized ultramafic body. The objective of this study is to determine the affinity of the rocks that host the mineralized ultramafic intrusion in southern Phillips Lake (e.g., Ospwagan group, Paint sequence, or Archean gneiss?). If it is shown that rocks of the Paint sequence can also host mineralized ultramafic intrusions, it will generate a new exploration target for companies working in the TNB.

Regional geology

The TNB forms a segment of the Superior boundary zone, flanked to the northwest by the Kisseynew domain of the Trans-Hudson orogen and to the southeast by the Pikwitonei granulite domain (PGD) of the Superior craton. The TNB is underlain largely by reworked Archean gneiss of the Superior craton, which is typically quartzofeldspathic with enclaves of mafic to ultramafic rock; clearly recognizable paragneiss is rare. The gneiss is commonly migmatitic and characterized by complex internal structures that are the result of multiple generations of Archean and Paleoproterozoic deformation and metamorphism. It is interpreted to be derived from the adjacent PGD, which was subjected to amphibolite- to granulite-facies metamorphic conditions ca. 2720 to 2640 Ma (Hubregtse, 1980; Mezger et al., 1990; Heaman et al., 2011; Guevara et al., 2016a, b). The granulites of the PGD were exhumed and unconformably overlain by the Paleoproterozoic supracrustal rocks of the Ospwagan group (TNB) prior to intrusion of the Molson dike swarm and associated ultramafic intrusions ca. 1883 Ma (Bleeker, 1990; Zwanzig et al., 2007; Heaman et al., 2009; Scoates et al., 2017). The Archean basement gneiss and Ospwagan group were subjected to multiple generations

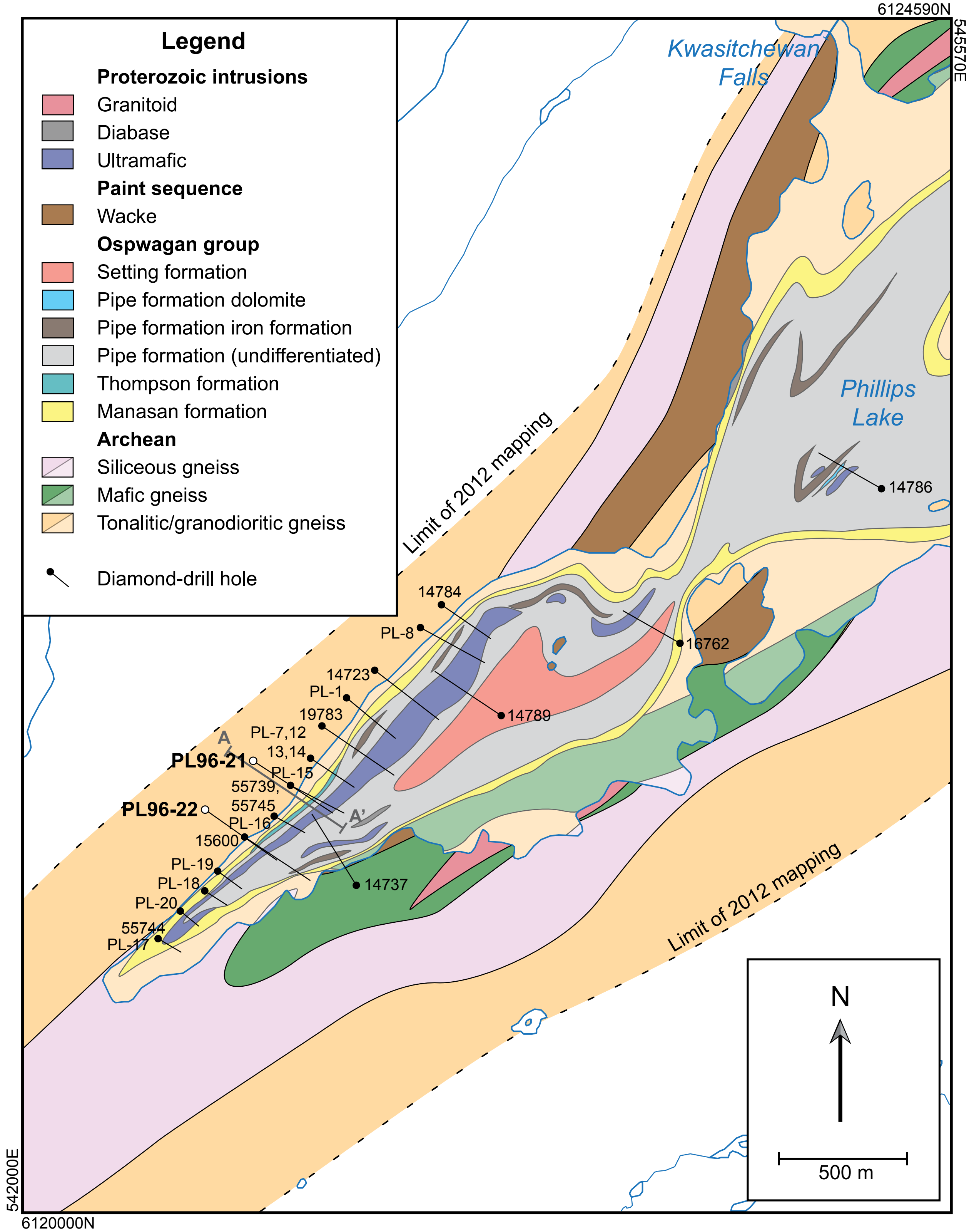

Figure GS2018-1-3: *Composite geology of southern Phillips Lake, showing the locations of diamond-drillholes by Inco Ltd. (five-digit numbers) and Falconbridge Ltd. (beginning with 'PL'). The geology underlying the lake is from Macek et al. (2006) and the shoreline geology is from Couëslan (2016). The section in Figure GS2018-1-2 is along line A–A' (in grey)* of deformation and metamorphic conditions, ranging from middle-amphibolite facies to lower-granulite facies, during the Trans-Hudson orogeny (Bleeker, 1990; Burnham et al., 2009; Couëslan and Pattison, 2012).

The dominant phase of penetrative deformation is D_2, which affected the Ospwagan group and ca. 1883 Ma magmatic rocks. This deformation phase resulted in the formation of F_2 nappe structures, which incorporated the underlying Archean gneiss. The nappe structures have been interpreted as either east verging (Bleeker, 1990; White et al., 2002) or southwest verging (Zwanzig et al., 2007; Burnham et al., 2009). The recumbent folds are associated with regionally penetrative S_2 fabrics. The D_2 phase of deformation is interpreted to be the result of convergence between the Superior craton margin and the Reindeer zone of the Trans-Hudson orogen ca. 1830 to 1800 Ma. The D_3 phase of deformation resulted in isoclinal folds with vertical to steeply southeast-dipping axial planes (Bleeker, 1990; Burnham et al., 2009). Mylonite zones with subvertical stretching lineations parallel many of the regional F_3 folds. Tightening of D_3 structures continued during D_4, marked by localized retrograde greenschist-facies metamorphism along northeast-striking, mylonitic and cataclastic shear zones that commonly record southeast-side-up sinistral movement (Bleeker, 1990; Burnham et al., 2009).

Ospwagan group stratigraphy

The following summary of the Ospwagan group is sourced largely from Bleeker (1990) and Zwanzig et al. (2007). The Paleoproterozoic Ospwagan group unconformably overlies Archean basement gneiss in the TNB (Figure GS2018-1-4). The lowermost unit of the Ospwagan group is the Manasan formation, which consists of two members: the lower M1 member, consisting of layered to laminated sandstone with local conglomerate layers near the base; and the overlying M2 member, consisting of semipelitic rock. The Manasan formation is interpreted as a transgressive, fining-upward sequence deposited along a passive margin. This siliciclastic system grades into the overlying calcareous sedimentary rocks of the Thompson formation.

The Thompson formation consists of three members: the T1 member comprises a variety of calcareous–siliceous rocks, including chert, calcsilicate and impure marble; the T2 member is a semipelitic calcareous gneiss that is rarely present; and the T3 member consists of impure dolomitic marble with local horizons of calcsilicate. The Thompson formation represents a transition from a siliciclastic-dominated to a carbonate-dominated system.

The Pipe formation is subdivided into three members. The P1 member consists of a graphite-rich, sulphide-facies iron formation at the base (the locus of the Pipe II and Birchtree orebodies), overlain by a silicate-facies iron formation. The top of the P1 member consists of a reddish, laminated, siliceous rock. The P1 member grades into the overlying pelitic rocks of the P2 member, the top of which is marked by a sulphide-facies iron formation (the locus of the Thompson orebody). The overlying P3 member consists of a wide variety of rock types, including laminated, siliceous, sedimentary rocks; silicate-, carbonate- and local oxide-facies iron formations; and semipelitic rocks, calcsilicate and a local horizon of relatively pure dolomitic marble. The Pipe formation represents a mix of chemical sediments and fine to very fine siliciclastics that were deposited in either an open-marine environment (Zwanzig et al., 2007) or during the development of a foredeep basin (Bleeker, 1990).

The Setting formation is divided into two members and is defined to include all siliciclastic rocks above the uppermost iron formation of the P3 member. The S1 member consists of rhythmically interbedded quartzite and pelitic schist with local calcareous concretions, which are characteristic of the S1 member. The S2 member consists of thickly layered greywacke, with local horizons grading from conglomeratic at the base to pelitic at the top. No contact has been observed between the S1 and S2 members. It is possible that they represent a lateral facies change as opposed to a vertical succession. The Setting formation is interpreted to have been deposited by turbidity currents in a relatively deep-marine environment, possibly a foredeep basin (Bleeker, 1990). The coarse clastic material and thick turbidite bedding of the S2 member may record the shallowing of the basin, the onset of active tectonism or a lateral sedimentary facies change to a submarine-channel or upper-fan environment (Zwanzig et al., 2007).

At the top of the Ospwagan group is the Bah Lake assemblage, which consists of mafic to ultramafic volcanic rocks dominated by massive to pillowed basalt flows with local picrite and minor synvolcanic intrusions. The Bah Lake assemblage is dominated by a high-Mg suite (similar to normal mid-ocean–ridge basalt; N-MORB) that occurs throughout much of the main TNB, and an incompatible-element–enriched suite (similar to enriched mid-ocean–ridge basalt; E-MORB) that occurs in the northwestern Setting Lake area and along the margin of the Kisseynew domain (Zwanzig, 2005). The enriched suite is interpreted to overlie the high-Mg suite; however, it is uncertain if this represents a stratigraphic or tectonic relationship. The Bah Lake assemblage may suggest the onset of active rifting in the TNB (Zwanzig, 2005; Zwan-

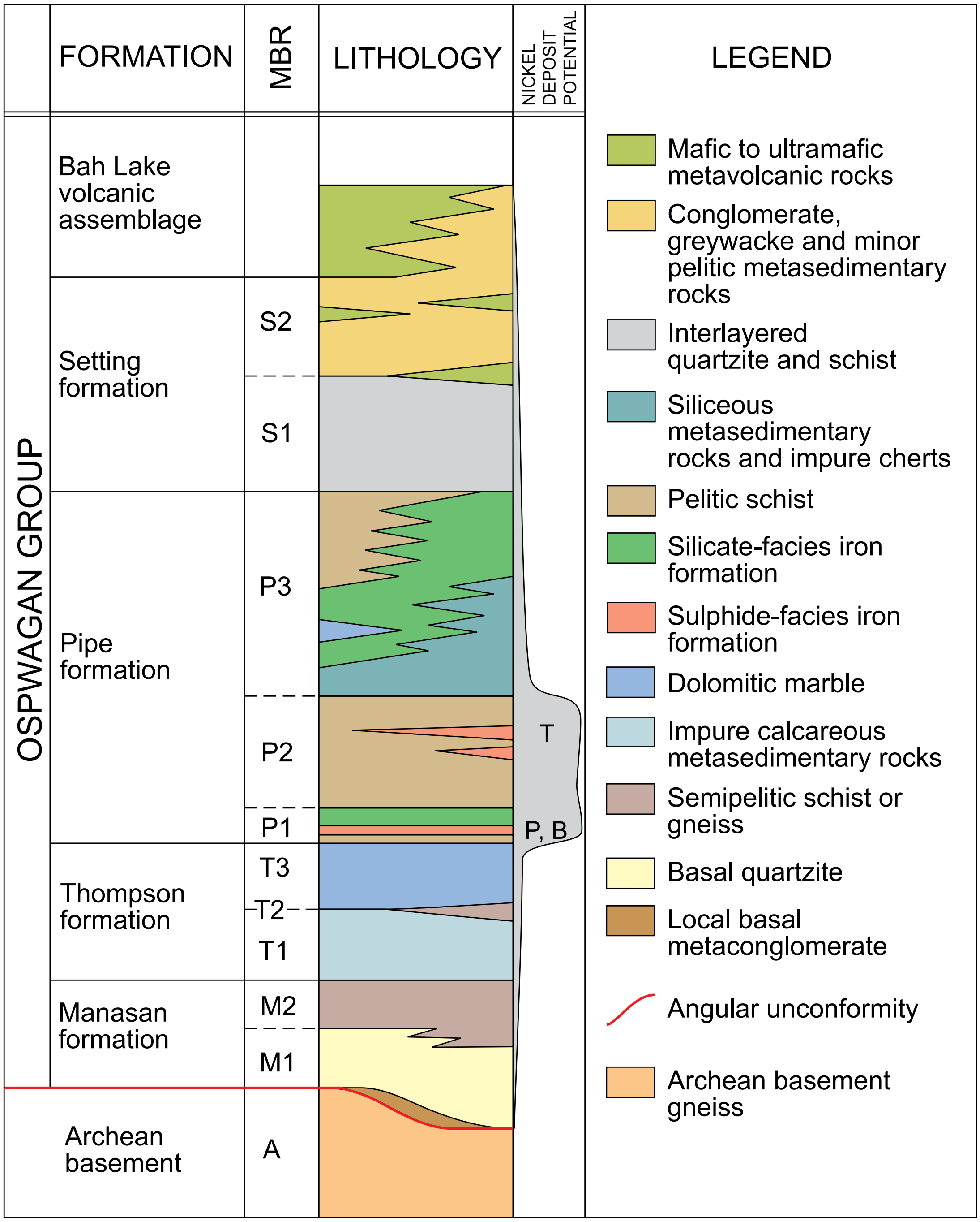

Figure GS2018-1-4: *Schematic lithostratigraphic section of the Ospwagan group (modified from Bleeker, 1990). Abbreviations: B, stratigraphic location of the Birchtree ore body; MBR, member; P, stratigraphic location of the Pipe II ore body; T, stratigraphic location of the Thompson ore body.*

zig et al., 2007), or that the foredeep was magmatically active (Bleeker, 1990).

A maximum age for the Ospwagan group is provided by a ca. 1974 Ma zircon recovered from Setting formation greywacke (Bleeker and Hamilton, 2001). A minimum age for the Ospwagan group is provided by crosscutting amphibolitized dikes interpreted to be part of the Molson dike swarm, and the possibly comagmatic Ni-ore–bearing ultramafic sills, which intruded the Ospwagan group at all stratigraphic levels ca. 1883 Ma (Bleeker, 1990; Zwanzig et al., 2007; Heaman et al., 2009; Scoates et al., 2017). Ospwagan group rocks yield crustal-residence Nd-model ages of ca. 3.22–2.82 Ga, which are typically younger than model ages obtained from the Archean basement (ca. 3.70–3.14 Ga; Böhm et al., 2007).

Granulite-facies assemblages in semipelitic and pelitic rocks of the Ospwagan group can become almost indistinguishable from the Archean basement gneiss; however, petrological end members such as marble, quartzite and iron formation remain recognizable at the highest metamorphic grades and can be used as marker horizons. Basement-like gneiss or migmatite successions between isolated but still recognizable marker horizons may represent 'ghost successions' of the Ospwagan group (Zwanzig et al., 2007). Distinguishing Archean from Ospwagan group rocks at high metamorphic grade may require the use of lithogeochemistry or Sm-Nd isotope geochemistry (Böhm et al., 2007; Zwanzig et al., 2007).

Paint sequence rocks

The 'Paint sequence' refers to three northeast-striking belts of metasedimentary rocks that occur in the Paint Lake area and appear to continue along strike to the Phillips Lake area (Couëslan, 2016). The stratigraphy of the Paint sequence is unconstrained but consists dominantly of wacke and psammite, with subordinate iron formation and pelite, and rare boudins of calcsilicate. To date, the Paint sequence has only been recognized in areas of granulite-facies metamorphism where primary textures and structures are all but obliterated save for centimetre-scale compositional layering. Wacke is the most abundant member of the sequence. It commonly contains centimetre- to decimetre-thick layers of psammite and iron formation. Pods of in situ to in-source leucosome are abundant. Outcrops of wacke are characterized by rusty weathered surfaces because of the presence of minor but ubiquitous pyrrhotite. The composition of the wacke and psammite are gradational into each other and they are commonly interbedded. The psammite is typically interlayered with centimetre- to metre-thick layers of wacke and rarely occurs interlayered with pelite. The iron formation occurs as discontinuous layers and lenses <3 m thick within the wacke. Iron formations are typically of the silicate facies; however, significant pyrrhotite and magnetite can be present. A maximum age for the Paint sequence is provided by five ca. 2436 Ma detrital zircon grains obtained from a sample of wacke (Couëslan, 2016). The Paint sequence rocks are intruded by relatively straight-walled mafic dikes, which are tentatively interpreted to be part of the Paleoproterozoic Molson dike swarm, suggesting a minimum age of ca. 1883 Ma for the sequence. The Paint sequence rocks contrast from the Ospwagan group rocks in having a distinct detrital zircon population, older crustal-residence Nd-model ages (ca. 3.57–3.23 Ga) and unique trace-element compositions (Couëslan, 2016).

Phillips Lake area

The Phillips Lake area is underlain by a highly attenuated basement dome (Burnham et al., 2009) consisting largely of Archean multicomponent gneiss, which comprises a mixture of tonalitic and granodioritic gneisses in varying proportions, with subordinate mafic and ultramafic phases (Macek et al., 2006; Couëslan, 2016). A thin sheet of Ospwagan group rocks mantles the dome and is thickened in the fold closure at the south end of Phillips Lake. Other, more discrete Archean units in the area include a mafic gneiss suite (Couëslan, 2016; amphibolitic gneiss), which could be derived from a layered gabbro complex (Macek, 1985) or possibly volcanic rocks (Couëslan, 2016); and a garnet- and magnetite-bearing siliceous gneiss unit. Rocks in the area attained granulite-facies metamorphic conditions during the Trans-Hudson orogeny, with orthopyroxene being a common constituent in rocks of felsic, intermediate and mafic bulk composition (Couëslan and Pattison, 2012).

Wacke and psammite, interpreted to be part of the Paint sequence, are exposed at Phillips Lake in the north arm, along the west shore south of Kwasitchewan Falls and in the central islands and the prominent point of the south basin (Figure GS2018-1-3; Couëslan, 2016). This is somewhat at odds with the mapping of Macek et al. (2006), which interpreted Ospwagan group rocks to underlie much of the south end of the lake, including the islands of the south basin. Several ultramafic bodies are hosted within the metasedimentary rocks. Discontinuous bodies and boudins of plagioclase amphibolite, ranging from centimetres to tens of metres across, are common in the area and are interpreted to represent metadiabase dikes. Intrusions of granodiorite and granitic pegmatite are also common, with pegmatite dikes present in almost all outcrops. The granitoid intrusions range in size from centimetres to tens of metres across and can be greater than 1 km in length (Couëslan, 2016).

Units

Two drillcores were selected for re-examination: PL96-21 and PL96-22. Both drillholes were collared in the hangingwall of the ultramafic body and drilled into the footwall (Figure GS2018-1-2). Units are described in order of intersection from top to bottom of the drillholes (Figure GS2018-1-5). All units are assumed to dip steeply to the west, and the stratigraphic younging direction is unknown. The core from each drillhole was laid out in its entirety, allowing for the entire sequence to be viewed and separated into petrographically distinct intervals. Each interval was described petrographically in the core logs, but they are presented here in a condensed, simplified

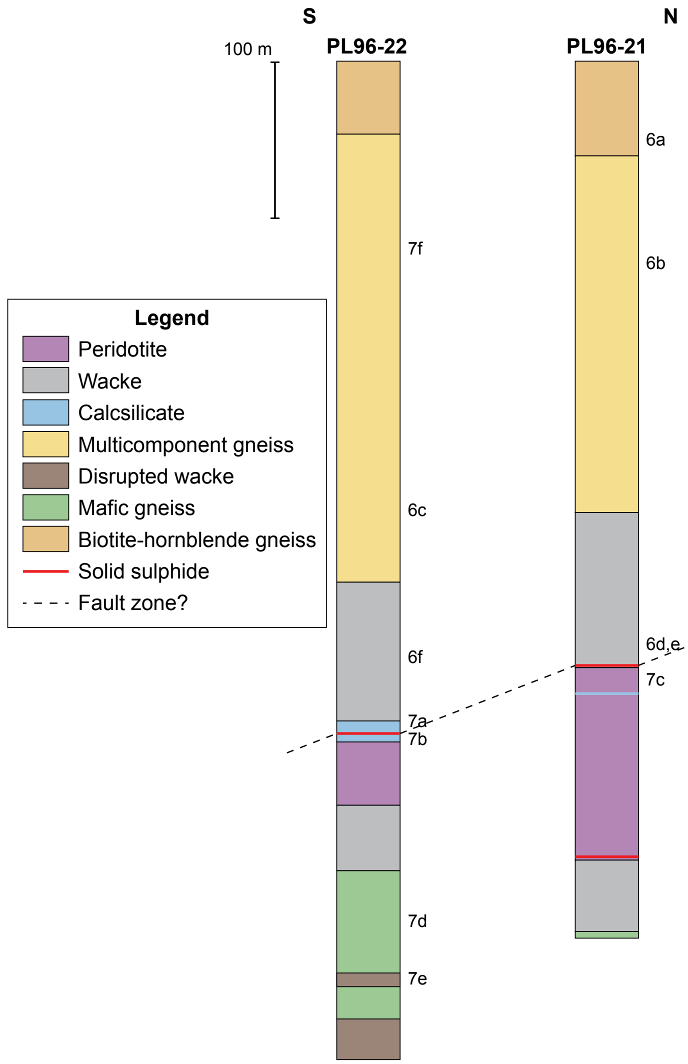

Figure GS2018-1-5: *Schematic logs of drillcores PL96-21 and PL96-22 in the southern Phillips Lake area; see Figure GS2018-1-3 for drillhole locations. The approximate locations of images in Figures GS2018-1-6 and GS2018-1-7 are indicated along the right-hand side of each column.*

form using protolith interpretation where appropriate. All rocks were metamorphosed to granulite facies, with orthopyroxene present in felsic, intermediate and mafic bulk compositions. All rocks, unless otherwise noted, are characterized by a well-developed penetrative foliation. Pods of leucosome, pegmatite injections and bands of plagioclase amphibolite are ubiquitous. Reported thicknesses are intersection lengths, not true thicknesses.

Biotite-hornblende gneiss

Both drillholes were collared in a 40–50 m thick interval of biotite-hornblende gneiss. The gneiss is grey to beige-grey and medium to coarse grained, and contains 3–5% hornblende and 7–15% biotite in a quartzofeldspathic groundmass (Figure GS2018-1-6a). Up to 3% garnet or 5% orthopyroxene is typically present, but they generally do not occur together. Interbanding of garnet-bearing and orthopyroxene-bearing gneisses typically occurs on a metre scale. This unit is tentatively interpreted as an orthogneiss and part of the Archean basement.

Multicomponent gneiss

Downhole from the biotite-hornblende gneiss is a 240–300 m thick interval of multicomponent gneiss. The gneiss is composed of a variety of phases, including various orthopyroxene-bearing gneisses likely derived from metamorphosed intrusive rocks; biotite-garnet and biotite-orthopyroxene gneisses likely derived from metamorphosed wackes; biotite-garnet and biotite-orthopyroxene gneisses of uncertain affinity; and a pink, orthopyroxene-free metasomatized gneiss. Although

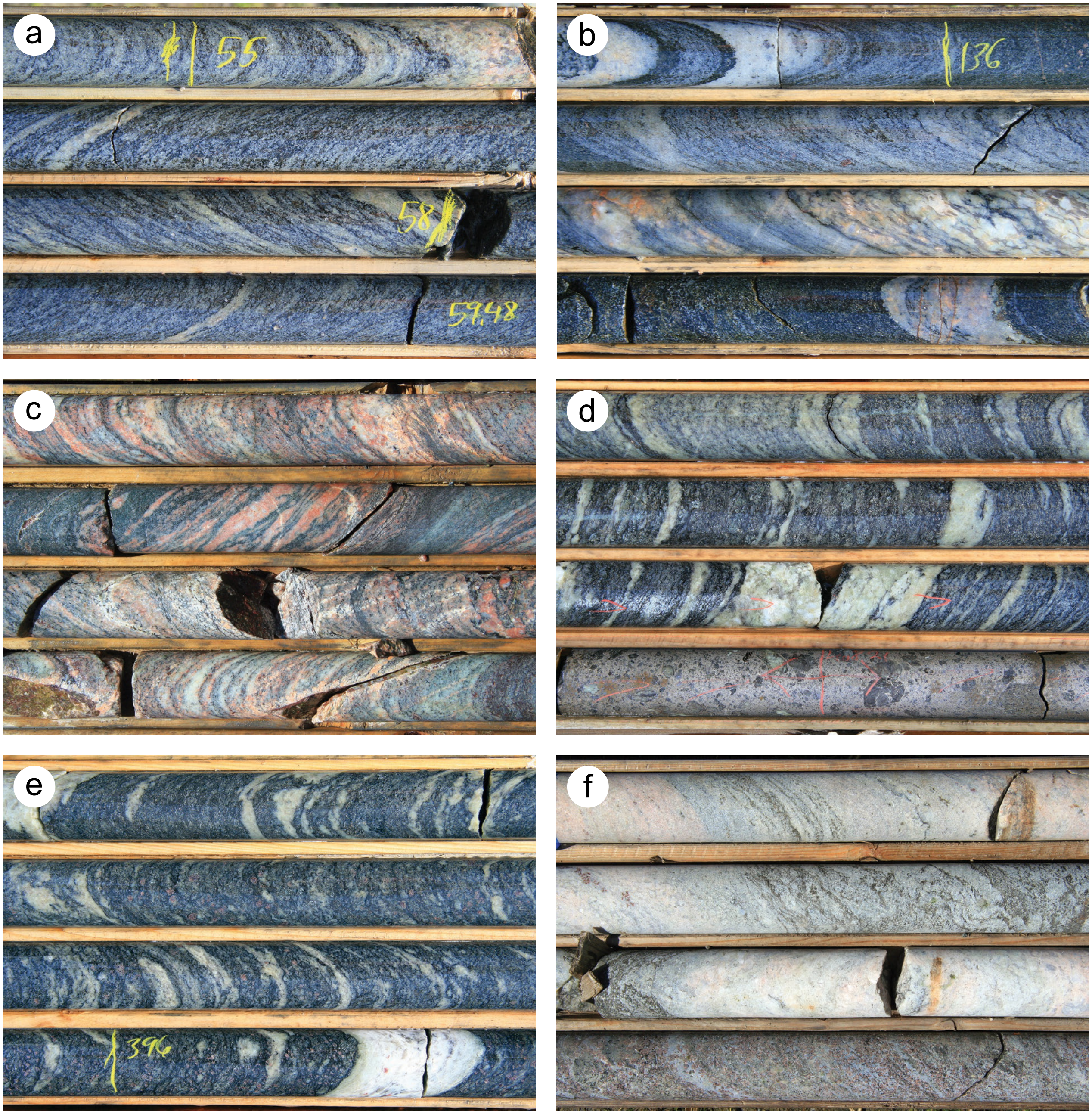

Figure GS2018-1-6: *Drillcore images from PL96-21 and PL96-22:* ***a)*** *biotite-hornblende gneiss (PL96-21, 54.9 m);* ***b)*** *multicomponent gneiss consisting of biotite-garnet gneiss of uncertain affinity (top two rows), sheared pegmatite (third row) and plagioclase amphibolite (bottom row; PL96-21, 135.7 m);* ***c)*** *metasomatized gneiss (PL96-22, 308.1 m);* ***d)*** *wacke-derived biotite-orthopyroxene gneiss (top three rows) with sulphide breccia (bottom row; PL96-21, 403.65 m);* ***e)*** *wacke-derived biotite-garnet gneiss (bottom three rows) and biotite-orthopyroxene gneiss (top row; PL96-21, 391.55 m);* ***f)*** *silicate-facies iron formation (bottom row) and pegmatite with schlieren of wacke-derived biotite-orthopyroxene gneiss (top three rows; PL96-22, 389.1 m). Drillcore is BQ with a diameter of 36.5 mm.*

intersections of discrete gneissic phases can be up to 81 m, as in the case for the metasomatized gneiss, the various gneissic phases are typically interlayered on a scale of <10 m. The gneisses are also intercalated with abundant layers of plagioclase amphibolite (<13 m) and granitic pegmatite (<56 m), and local layers of ultramafic amphibolite (<1.5 m; Figure GS2018-1-6b). The metasomatized gneiss appears to be an amphibolitized equivalent of the other gneiss varieties and may contain more abundant injections of granitic pegmatite (Figure GS2018-1-6c). The multicomponent gneiss likely represents a tectonic interleaving of various Archean and Proterozoic gneissic phases intruded by Paleoproterozoic diabase and granitic pegmatite intrusions. Intercala-

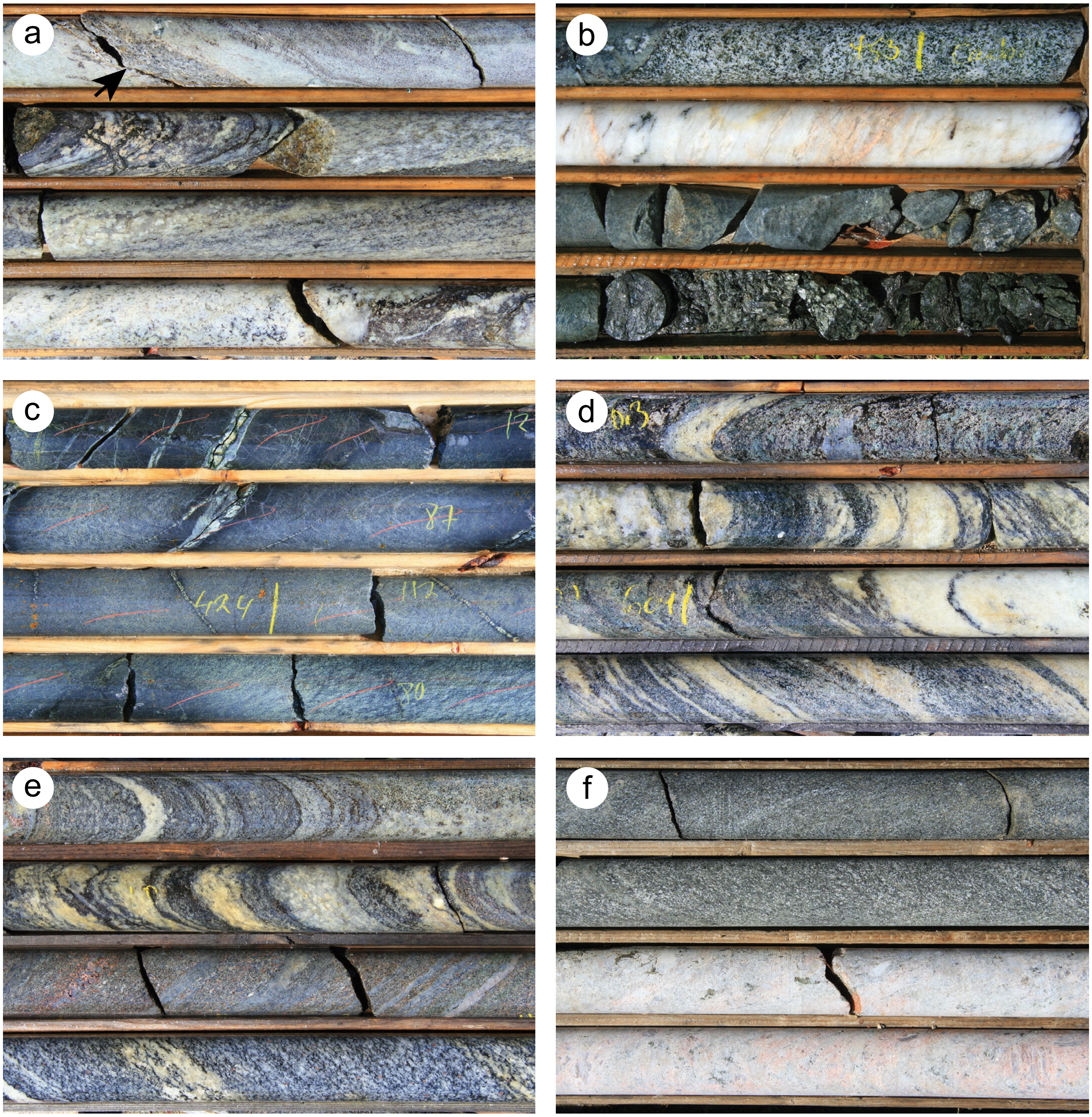

Figure GS2018-1-7: *Drillcore images from PL96-21 and PL96-22:* ***a)*** *calcsilicate with layer of phlogopite marble (arrow, top row) and sheared pegmatite (bottom three rows; PL96-22, 441 m);* ***b)*** *olivine marble (top row), sheared pegmatite (second row), serpentinized peridotite (third row) and ultramafic schist (bottom row; PL96-22, 452.8 m);* ***c)*** *serpentinized peridotite (PL96-21, 421.5 m);* ***d)*** *mafic gneiss (PL96-22, 601 m);* ***e)*** *disrupted wacke (biotite-garnet gneiss, top two rows), well-layered iron formation (third row) and garnet-bearing granodiorite (bottom row; PL96-22, 623 m);* ***f)*** *plagioclase amphibolite (top two rows) and pegmatite (bottom two rows; PL96-22, 122 m). Drillcore is BQ with a diameter of 36.5 mm.*

tions of the wacke-derived, biotite-orthopyroxene gneiss become increasingly abundant in the bottom 25 m of the multicomponent gneiss interval in drillhole PL96-21.

Wacke

Downhole from the multicomponent gneiss is a 95–107 m thick interval of wacke. The wacke consists of interlayered biotite-orthopyroxene gneiss (Figure GS2018-1-6d) and biotite-garnet gneiss (Figure GS2018-1-6e), with local intercalations of silicate-facies iron formation. The biotite-orthopyroxene gneiss is grey to beige and medium to coarse grained, with diffuse layering 2–5 cm thick. The gneiss contains 20–30% mafic minerals dominated by biotite with <10% orthopyroxene, and rarely minor hornblende, in a quartzofeldspathic groundmass. Trace amounts of pyrrhotite and magnetite can also be present. The biotite-garnet gneiss is similar in overall appearance but contains <5% garnet. Intervals of wacke may be dominated by one variety of gneiss over the other, or they may occur in roughly equal proportions interlayered on a decimetre to metre scale.

Intercalations of silicate-facies iron formation <70 cm thick are present within the wacke-derived gneisses. The iron formation is dark purplish green, coarse grained and magnetic. It is relatively massive, with diffuse layering, <15 cm thick, defined by varying proportions of the mafic minerals that typically make up <50% of the rock. Mafic minerals are dominated by garnet and orthopyroxene, with <7% biotite and minor magnetite and pyrrhotite. The groundmass is relatively siliceous. Sparse chert layers are poorly developed and typically <1 cm thick (Figure GS2018-1-6f).

Calcsilicate and marble

A 14 m wide intersection of calcsilicate and marble occurs downhole from the wacke in the drillcore from PL96-22. The calcsilicate is light green and fine to coarse grained, with diffuse, <10 cm thick layering. The rock contains <12% phlogopite and 30–40% diopside in a groundmass of quartz, feldspar and carbonate. The calcsilicate contains sparse layers, <20 cm thick, of strongly foliated phlogopite marble (Figure GS2018-1-7a). A single 30 cm thick layer of olivine marble occurs toward the bottom of the interval (Figure GS2018-1-7b). The olivine marble is pale grey-green, medium grained and weakly foliated. It contains 10–20% serpentinized olivine and 5–7% phlogopite, with minor amounts of diopside.

Calcsilicate is also present as a 1.4 m wide band of tremolite-biotite gneiss hosted by peridotite in PL96-21. The gneiss is purplish grey and fine grained, with diffuse layering <3 cm thick. The gneiss appears to be quartzofeldspathic, with 10–20% tremolite and 5–7% biotite, and is interpreted as a xenolith within the ultramafic intrusion.

Sulphide breccia

A 70 cm thick zone of sulphide breccia occurs within the calcsilicate interval in PL96-22. The breccia consists of a near-solid pyrrhotite matrix surrounding 7–10% rounded to subangular quartzofeldspathic fragments <2 cm across, and 20–30% biotite schist fragments <10 cm across. The biotite schist fragments vary from rounded to angular and commonly display diffuse margins. A similar 1 m interval of sulphide breccia occurs within the wacke, immediately above the peridotite intrusion in PL96-21, and contains 3–5% ultramafic amphibolite fragments <2 cm across, 5–7% rounded graphite grains <1.5 cm across, and 7–10% rounded to subangular quartzofeldspathic fragments <2 cm across (Figure GS2018-1-6d). The sulphide breccia could be correlative between the two drillholes. Sheared to mylonitic rocks are associated with the breccia in both drillholes, suggesting the breccia likely represents structurally remobilized sulphide in a shear zone or fault. Falconbridge reported assays from both intervals to be barren (0.071% Ni in PL96-21, 0.095% Ni in PL96-22; Assessment File 94497).

Peridotite

The wacke is intruded by a 44–136 m thick interval of serpentinized peridotite (Figure GS2018-1-7c). The peridotite is black to green, medium to coarse grained and strongly magnetic. It contains serpentine and minor magnetite and sulphide. The sulphide generally occurs as fine disseminated grains; however, toward the bottom of the interval in PL96-21, the sulphide content increases to as much as 5% and occurs as segregations up to 1 cm across. Relict texture suggests that cumulate olivine were <1 cm across. Bands of ultramafic schist <1.5 m thick are common within the serpentinized peridotite (Figure GS2018-1-7b). The ultramafic schist is silvery grey-green, coarse grained and nonmagnetic. It consists of anthophyllite, with variable amounts of phlogopite, chlorite and clinoamphibole typically forming <40% of the rock. The ultramafic schist commonly occurs at the contacts of crosscutting pegmatite dikes. A 60 cm wide zone of solid sulphide near the base of the peridotite in PL96-21 yielded 6.07% Ni over 0.57 m in Falconbridge assays (Assessment File 94497). The solid sulphide consists dominantly of pyrrhotite, with 10–20% biotite, 5–7% pentlandite and 2–3% quartzofeldspathic fragments <10 cm across. A 43–51 m thick interval of wacke continues downhole from the ultramafic intrusion.

Mafic gneiss

Downhole from the wacke in PL96-22 is a 107 m thick package of mafic gneiss (Figure GS2018-1-7d). The gneiss is green-grey, medium to coarse grained and nonmagnetic, with diffuse banding <1 m thick. The rock is relatively heterogeneous, with abundant leucosome and a beige plagioclase-rich groundmass. Mafic mineral contents vary from 40–75%, consisting of varying proportions of orthopyroxene, clinopyroxene and green hornblende, along with minor biotite. Large portions of the interval are amphibolitized, with all mafic minerals reacted to form black hornblende±biotite, and the plagioclase becoming white in colour. Drillhole PL96-21 terminates in a similar, largely amphibolitized unit that is likely correlative. The mafic gneiss is petrographically similar to the high-Mg amphibolitic gneiss previously described in the Paint and Phillips lakes area (Couëslan, 2016).

Disrupted wacke

A 7.8 m thick intersection of garnet-bearing wacke, with minor iron formation as bands <80 cm thick, occurs within the mafic gneiss interval in PL96-22 (Figure GS2018-1-7e). The wacke and iron formation appear texturally distinct from those previously described. The wacke is largely disrupted by leucosome and/or pegmatite injection, and the iron formation is well layered, with alternating ferruginous and cherty layers <7 cm thick. Ferruginous minerals make up 30–50% of the rock and consist of roughly equal proportions of magnetite and orthopyroxene, and <10% garnet. The iron formation also contains sparse grains of pyrrhotite <2 cm across. Disrupted wacke continues for another 30 m downhole, below the mafic gneiss.

Other intrusive phases

Intersections of plagioclase amphibolite <13 m thick are ubiquitous in the drillcore (Figure GS2018-1-7f). The amphibolite is dark green-grey, medium to coarse grained and relatively homogeneous. It contains 50–70% hornblende in a groundmass of plagioclase and quartz; orthopyroxene is locally present and garnet is rare. In a few locations, the amphibolite is zoned, with medium-grained margins and coarse-grained, more mafic cores (90–95% hornblende). The plagioclase amphibolite is interpreted as metamorphosed diabase and gabbro dikes, possibly related to the Molson dike swarm.

Intrusions of granitic pegmatite <56 m wide are also ubiquitous in the drillcore (Figure GS2018-1-6b, f; Figure GS2018-1-7a, b, f). The pegmatite is typically pink, with <2% biotite and rare garnet, orthopyroxene and magnetite. Locally derived schlieren are common. The pegmatite is often sheared to protomylonitic. Pegmatite associated with the calcsilicate, serpentinized peridotite and mafic gneiss is commonly white.

Geochemistry

Twenty-four samples, representing most of the major units, were collected for lithogeochemistry; however, this section will focus on the potential metasedimentary rocks (wacke, calcsilicate and iron formation). The samples were crushed and pulverized at the MGS's Midland Sample and Core Library, and the homogenized pulps were submitted to Activation Laboratories Ltd. (Ancaster, Ontario). The pulps were fused with lithium metaborate/tetraborate, followed by a nitric-acid digestion, and analyzed by inductively coupled plasma–emission spectrometry (ICP-ES) for the major elements and selected trace elements (Ba, Be, Sc, Sr, V, Y, Zr), and by inductively coupled plasma–mass spectrometry (ICP-MS) for the remaining trace elements and the rare-earth elements (REE). Samples of calcsilicate and marble were analyzed for carbon, and wacke and iron formation were analyzed for carbon and sulphur, through induction-furnace combustion and measurement of the release of CO_2 and SO_2 by infrared spectrometry.

Because of the high metamorphic grade, the wacke was subjected to intense partial melting. Therefore, wacke samples were selected that appear representative of the bulk composition in terms of proportion of leucosome to melanosome or mesosome, and care was taken to avoid apparent injected leucosome in favour of material that appeared to consist of in situ or in-source leucosome. The calcareous sedimentary rocks and iron formation underwent minimal partial melting, so care was taken to sample material with little to no leucosome.

The use of trace elements is restricted to those interpreted to be less mobile in the high-grade metamorphic environment, including selected transition metals (Sc, V, Cr, Ni), high-field-strength elements (HFSE; Ti, Zr, Nb), REE and Th. However, it should be noted that Th may partition into silicate melt, the removal of which could result in the depletion of Th.

Wacke

Whole-rock geochemical data for the wacke were normalized to the average P2 member pelite of the Pipe formation and plotted on multi-element diagrams, as outlined in Zwanzig et al. (2007). Normalized profiles for the Paint sequence wacke are relatively flat, with negative anomalies at Nb and Zr, and elevated V, Sc and especially Cr relative to the adjacent heavy rare-earth elements (HREE; Figure GS2018-1-8a). Thorium is characterized by significant variability, a potential consequence of intense partial melting. The majority of wacke samples from the Phillips Lake core show similar normalized profiles, although two samples have profiles with distinct negative slopes for the REE (Figure GS2018-1-8b). This contrasts with semipelitic to pelitic rocks of the Ospwagan group, which are characterized by relatively flat P2-normalized profiles, with some variability at Zr and Sc, and no positive anomalies at Cr (Figure GS2018-1-8c–e). The normalized profiles of the Phillips Lake wacke suggest a greater affinity to the Paint sequence wacke than to the pelitic to semipelitic rocks of the Ospwagan group. The elevated values for V, Sc and Cr in the Paint sequence and Phillips

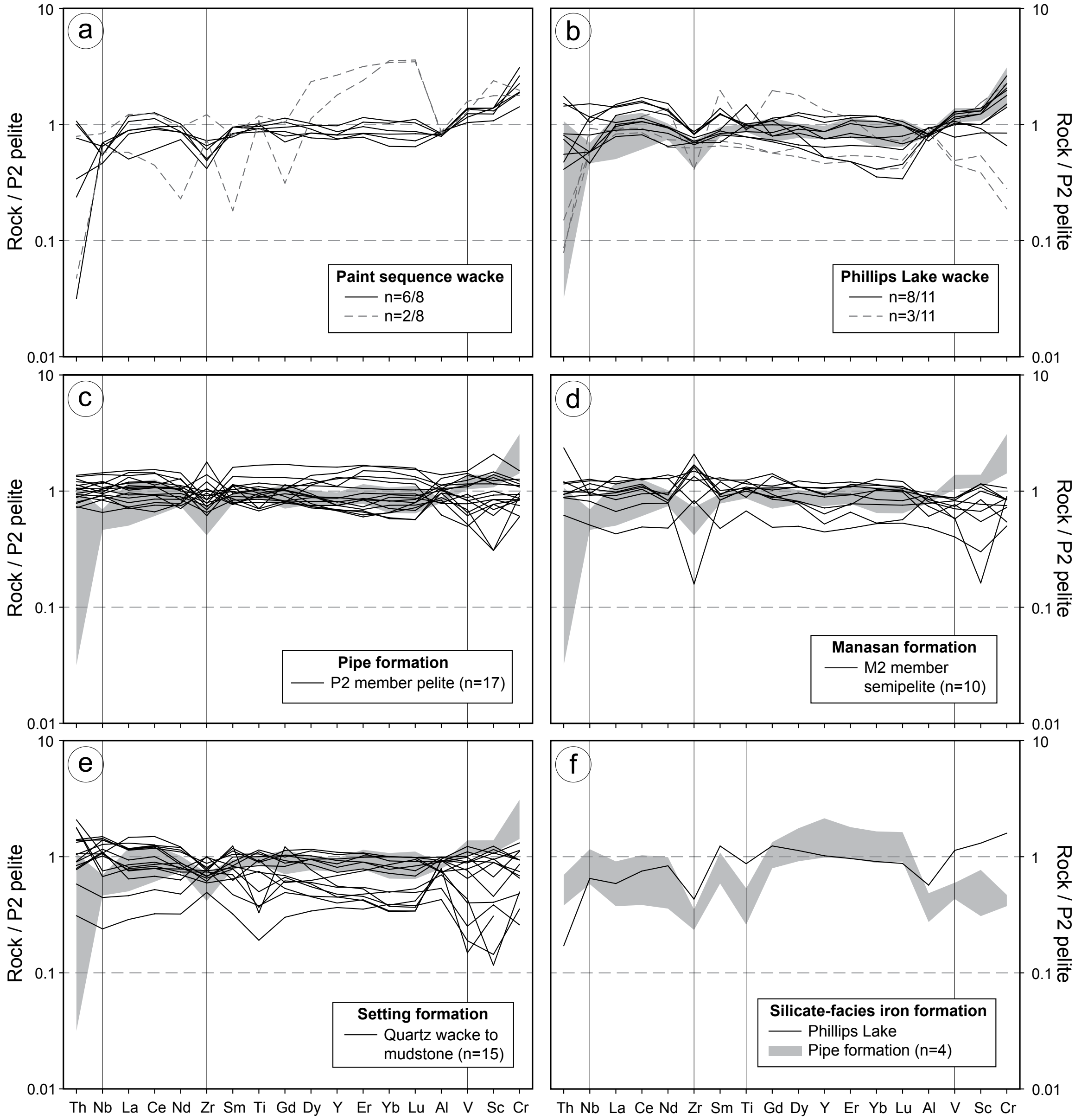

Figure GS2018-1-8: *Multi-element diagrams normalized to average P2 of Zwanzig et al. (2007):* ***a)*** *Paint sequence wacke from Paint Lake;* ***b)*** *wacke from Phillips Lake;* ***c)*** *Pipe formation P2 member pelite;* ***d)*** *Manasan formation M2 member semipelite;* ***e)*** *Setting formation quartz wacke to mudstone;* ***f)*** *Phillips Lake and Pipe formation silicate-facies iron formation. Dashed profiles are considered to be atypical. The grey fields in (b) to (e) denote typical Paint sequence wacke. Geochemical data for the Paint sequence wacke are from Couëslan (2016) and data for Ospwagan group rocks are from Zwanzig et al. (2007) and Couëslan (2016, unpublished data, 2012).*

Lake wackes could indicate a detrital source with a greater proportion of mafic rocks.

A sample of Phillips Lake silicate-facies iron formation, found interbedded with the wacke, has a P2-normalized profile that is concave down for the REE, with negative anomalies at Zr, Ti and Al, a positive anomaly at Nb, and elevated V, Sc, and Cr (Figure GS2018-1-8f). Normalized profiles for Pipe formation silicate-facies iron formation have slight positive slopes for the REE, negative anomalies at Zr, Ti and Al, and positive anomalies at Nb and Y. Values for V, Sc and Cr are below those of the HREE. The silicate-facies iron formation from Phillips Lake appears to be geochemically distinct from Pipe formation silicate-facies iron formation. The elevated V, Sc and Cr in the Phillips Lake iron formation are likely related to a siliciclastic component inherited from the same source as the wacke.

Calcsilicate and marble

The P2-normalized multi-element profiles for Phillips Lake calcsilicate are relatively flat to slightly concave down for the REE, and characterized by negative anomalies at Th, Zr, Ti and Al, and a positive anomaly at Sc in one sample and Y in the other (Figure GS2018-1-9a). Normalized profiles for Thompson formation calcsilicate are relatively flat to slightly concave down for the REE, and characterized by positive anomalies at Zr and Sc, and a slight negative anomaly at Ti. The Phillips Lake phlogopite marble is characterized by a relatively flat to slightly concave-down profile, with a negative anomaly at Al and a positive anomaly at Sc (Figure GS2018-1-9b). Normalized profiles for Thompson formation phlogopite marble are also slightly concave down, generally with positive anomalies at Zr and Sc, a negative anomaly at Ti and depleted V, Sc and Cr relative to HREE. The Phillips Lake olivine marble is characterized by a profile with a positive slope, is depleted in Th, Nb, Ti, Al, V and Sc, and has a positive anomaly at Y (Figure GS2018-1-9c). Normalized profiles for the Thompson formation olivine marble are variable with generally positive slopes, a positive anomaly at Y and depletions in Ti, Al, V and Sc. Chromium was below detection limits in all of the olivine marble samples. Normalized profiles for Phillips Lake and Thompson formation calcareous rocks are similar overall, although slight differences do exist, most notably the lack of a positive Zr anomaly in the Phillips Lake calcsilicate and phlogopite marble; however, the sample size is too small for a statistically meaningful comparison. Additional work is required to determine the affinity of the calcsilicate rocks on Phillips Lake for either the Ospwagan group or the Paint sequence.

Economic considerations

The most widely accepted model for generating Ni-Cu deposits in the TNB invokes the intrusion of ultramafic magmas into sulphide-rich horizons of the Ospwagan group Pipe formation (Figure GS2018-1-4). The magmas then scavenged sulphide from the host sedimentary rocks, leading to sulphur saturation of the melt and the precipitation and concentration of sulphides enriched in Ni and Cu. As a result, ultramafic bodies hosted by Pipe formation rocks are considered the most likely to host mineralization and are therefore prime exploration targets in the TNB (Bleeker, 1990; Zwanzig et al., 2007). The recently recognized Paint sequence consists of sulphide-

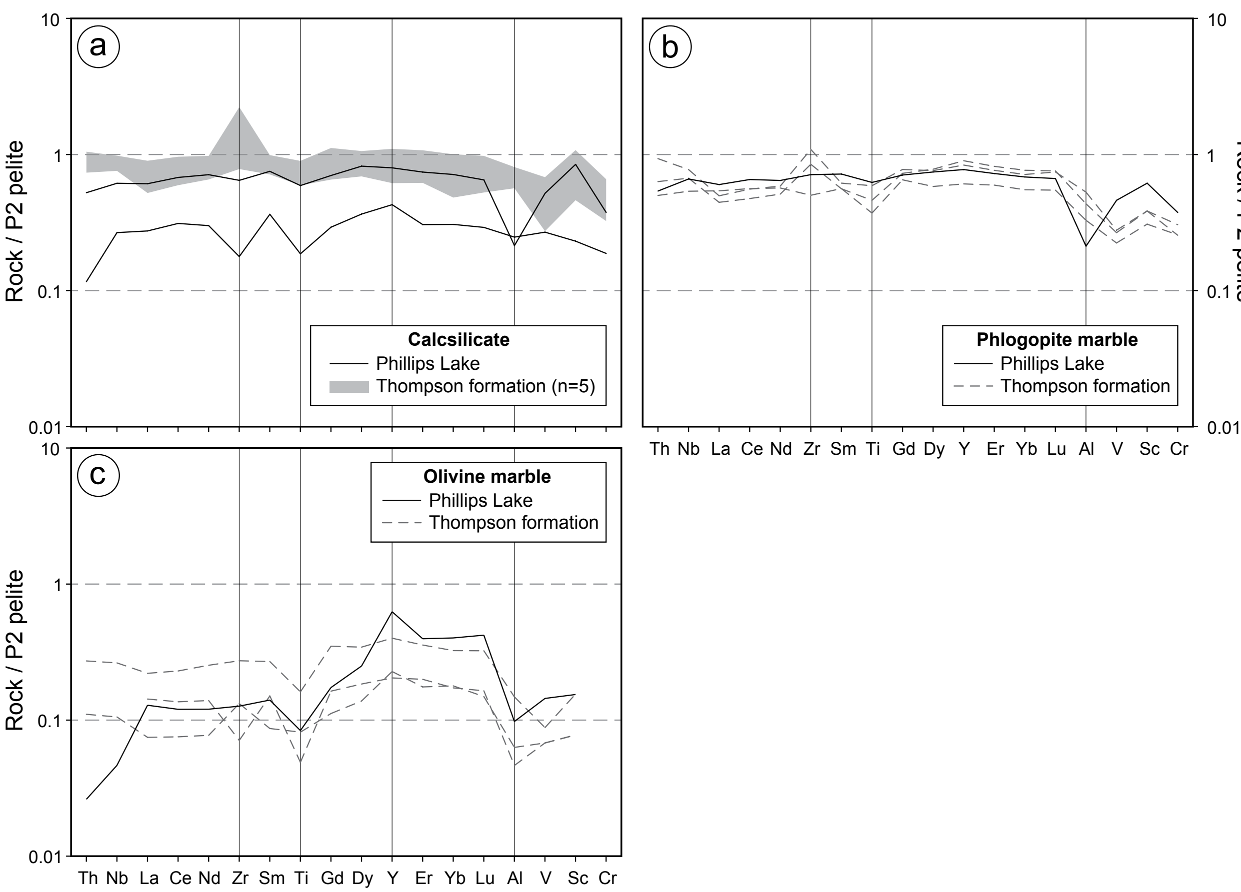

*Figure GS2018-1-9: Multi-element diagrams normalized to average P2 of Zwanzig et al. (2007): **a)** Phillips Lake and Thompson formation calcsilicates; **b)** Phillips Lake and Thompson formation phlogopite marbles; **c)** Phillips Lake and Thompson formation olivine marbles. Thompson formation geochemical data are from Couëslan (2003, 2016) and Zwanzig et al. (2007).*

bearing wacke and psammite with minor iron formation. The presence of sedimentary sulphide in this sequence suggests a notional potential to host mineralized ultramafic intrusions (Couëslan, 2016).

Preliminary results suggest that the wacke hosting the mineralized peridotite at Phillips Lake is likely part of the Paint sequence. This suggests that, in addition to the Ospwagan group, the Paint sequence is capable of hosting mineralized ultramafic intrusions; however, the matter is complicated by the presence of the calcareous sedimentary rocks of uncertain affinity. The two most likely scenarios for the calcareous rocks are that 1) they represent a tectonic sliver of Ospwagan group rocks spatially associated with the Paint sequence wacke, or 2) they are part of the Paint sequence. In the first scenario, the calcareous rocks could be part of the Thompson formation, with the spatially associated sulphide breccia potentially representing Pipe formation, P1 member sulphide-facies iron formation (Figures GS2018-1-4, -5). In this scenario, the mineralized peridotite is in direct contact with Ospwagan group rocks, at a similar stratigraphic level to that of the Pipe II and Birchtree ore bodies. The close spatial association of the Paint sequence wacke would in this case be coincidental and possibly of little consequence with respect to Ni mineralization. In the second scenario, the mineralized peridotite is hosted entirely in Paint sequence rocks, suggesting that ultramafic rocks hosted by the Paint sequence could be a new exploration target in the TNB. Rare boudins of calcsilicate are present in the Paint sequence rocks at Paint Lake, suggesting this could be a possibility. These preliminary results are ambiguous. It is hoped that the affinity of the calcareous rocks can be constrained through further lithogeochemical and Sm-Nd isotopic analyses.

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References

Bleeker, W. 1990: Evolution of the Thompson Nickel Belt and its nickel deposits, Manitoba, Canada; Ph.D. thesis, University of New Brunswick, Fredericton, New Brunswick, 400 p.

Bleeker, W. and Hamilton, M.A. 2001: New SHRIMP U-Pb ages for the Ospwagan group: implications for the SE margin of the Trans-Hudson orogen; Geological Association of Canada–Mineralogical Association of Canada 2001, Joint Annual Meeting, St. John's, Newfoundland, May 27–30, 2001, Abstracts, v. 26, p. 15.

Böhm, C.O., Zwanzig, H.V. and Creaser, R.A. 2007: Sm-Nd isotope technique as an exploration tool: delineating the northern extension of the Thompson Nickel Belt, Manitoba, Canada; Economic Geology, v. 102, p. 1217–1231.

Burnham, O.M., Halden, N., Layton-Matthews, D., Lesher, C.M., Liwanag, J., Heaman, L., Hulbert, L., Machado, N., Michalak, D., Pacey, M., Peck, D.C., Potrel, A., Theyer, P., Toope, K. and Zwanzig, H. 2009: CAMIRO project 97E-02, Thompson Nickel Belt: final report, March 2002, revised and updated 2003; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Open File OF2008-11, 434 p. plus appendices and GIS shape files for use with ArcInfo®.

Couëslan, C.G. 2003: Petrogenesis of the Thompson Formation T1 Member, Thompson Nickel Belt, Manitoba; B.Sc. thesis, Brandon University, Brandon, Manitoba, 126 p.

Couëslan, C.G. 2012: The Grass River Project: geological mapping at Phillips Lake, and new geochronological results from Paint Lake and Manasan Falls, Thompson Nickel Belt, central Manitoba (parts of NTS 63O1, 8, 9, 63P5, 12); *in* Report of Activities 2012, Manitoba Innovation, Energy and Mines, Manitoba Geological Survey, p. 68–78.

Couëslan, C.G. 2016: Geology of the Paint and Phillips lakes area, Thompson nickel belt, central Manitoba (parts of NTS 63O1, 8, 9, 63P5, 12); Manitoba Growth, Enterprise and Trade, Manitoba Geological Survey, Geoscientific Report GR2016-1, 44 p. and 1 colour map at 1:50 000 scale.

Couëslan, C.G. and Pattison, D.R.M. 2012: Low-pressure regional amphibolite-facies to granulite-facies metamorphism of the Paleoproterozoic Thompson Nickel Belt, Manitoba; Canadian Journal of Earth Sciences, v. 49, p. 1117–1153.

Guevara, V.E., Dragovic, B., Caddick, M.J., Kylander-Clark, A.R.C. and Couëslan, C.G. 2016a: Ultrahigh temperature metamorphism of the Archean Pikwitonei granulite domain; Geological Society of America, Annual Meeting, Denver, Colorado, September 25–28, 2016, Abstracts with Programs, v. 48, Paper 270-4, URL <https://gsa.confex.com/gsa/2016AM/webprogram/Paper284904.html> [October 2018].

Guevara, V., MacLennan, S.A., Schoene, B., Dragovic, B., Caddick, M.J., Kylander-Clark, A.R. and Couëslan, C.G. 2016b: Quantifying the timescales of Archean UHT metamorphism through U-Pb monazite and zircon petrochronology; American Geophysical Union, Fall Meeting, San Francisco, California, December 12–16, 2016, Abstract V51B-07, URL <https://agu.confex.com/agu/fm16/meetingapp.cgi/Paper/175259> [October 2018].

Heaman, L.M., Böhm, C.O., Machado, N., Krogh, T.E., Weber, W. and Corkery, M.T. 2011: The Pikwitonei Granulite Domain, Manitoba: a giant Neoarchean high-grade terrane in the northwest Superior Province; Canadian Journal of Earth Sciences, v. 48, p. 205–245.

Heaman, L.M., Peck, D. and Toope, K. 2009: Timing and geochemistry of 1.88 Ga Molson Igneous Events, Manitoba: insights into the formation of a craton-scale magmatic and metallogenic province; Precambrian Research, v. 172, p. 143–162, https://doi.org/10.1016/j.precamres.2009.03.015.

Hubregtse, J.J.M.W. 1980: The Archean Pikwitonei granulite domain and its position at the margin of the northwestern Superior Province (central Manitoba); Manitoba Energy and Mines, Manitoba Geological Survey, Geological Paper GP80-3, 16 p.

Macek, J.J. 1985: Geological investigations in the Phillips Lake area (part of 63O/12); *in* Report of Field Activities, Manitoba Energy and Mines, Geological Services, p. 181–182.

Macek, J.J., Zwanzig, H.V. and Pacey, J.M. 2006: Thompson Nickel Belt geological compilation map, Manitoba (parts of NTS 63G, J, O, P and 64A and B); Manitoba Science, Technology, Energy, and Mines, Manitoba Geological Survey, Open File Report OF2006-33, digital map on CD.

McGregor, C.R., Macek, J.J. and Zwanzig, H.V. 2006: Reinterpretation of Falconbridge Limited drillcore from the southern part of the exposed Thompson Nickel Belt, Manitoba (parts of NTS 63J, O, P and 64A), and criteria for recognizing lithologic units of the Ospwagan Group; Manitoba Science, Technology, Energy, and Mines, Manitoba Geological Survey, Open File Report OF2006-31, 1 DVD.

Mezger, K., Bohlen, S.R. and Hanson, G.N. 1990: Metamorphic history of the Archean Pikwitonei granulite domain and the Cross Lake subprovince, Superior Province, Manitoba, Canada; Journal of Petrology, v. 31, p. 483–517.

Scoates, J.S., Scoates, J.R.F., Wall, C.J., Friedman, R.M. and Couëslan, C.G. 2017: Direct dating of ultramafic sills and mafic intrusions associated with Ni-sulfide mineralization in the Thompson nickel belt, Manitoba, Canada; Economic Geology, v. 112, p. 675–692.

White, D.J., Lucas, S.B., Bleeker, W., Hajnal, Z., Lewry, J.F. and Zwanzig, H.V. 2002: Suture-zone geometry along an irregular Paleoproterozoic margin: the Superior boundary zone, Manitoba, Canada; Geology, v. 30, p. 735–738.

Zwanzig, H.V. 2005: Geochemistry, Sm-Nd isotope data and age constraints of the Bah Lake assemblage, Thompson Nickel Belt and Kisseynew Domain margin: relation to Thompson-type ultramafic bodies and a tectonic model (NTS 63J, O and P); *in* Report of Activities 2005, Manitoba Industry, Economic Development and Mines, Manitoba Geological Survey, p. 40–53.

Zwanzig, H.V., Macek, J.J. and McGregor, C.R. 2007: Lithostratigraphy and geochemistry of the high-grade metasedimentary rocks in the Thompson Nickel Belt and adjacent Kisseynew Domain, Manitoba: implications for nickel exploration; Economic Geology, v. 102, p. 1197–1216.