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The geology, geochemistry, and petrogenesis of the Huckleberry Cu-Ni-PGE prospect in the Labrador Trough, Canada: Perspectives for regional prospectivity

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The Palaeoproterozoic Huckleberry Cu-Ni-(PGE) prospect in the Labrador Trough, northern Québec, represents a ~ 400-m-thick, out-of-sequence sill complex that comprises a ~ 200-m-thick glomeroporphyritic gabbro, intruded in its centre by a ~ 200-m-thick differentiated gabbro-peridotite sill and in its gabbroic footwall, several thinner (< 30 m) ultramafic sills. Globular sulphides are present at the base of the sill complex, whereas disseminated to net-textured sulphides occur in the ultramafic units (Cu/Ni = 0.1-0.8) as well as their gabbroic footwall (Cu/Ni = 1-3). The glomeroporphyritic gabbro sill stack (MgO ~ 4 wt.%, TiO$_2$ ~ 0.6 wt.%, Na$_2$O+K$_2$O ~ 2-3%, Eu/Eu* ~ 1.2, An$_{plg}$ ~ 70-60) comprises several sills characterised by sharp changes in size and abundance of plagioclase glomerocrysts. We hypothesise that the glomerocrysts represent remobilised crystal mushes that were dislodged from a floatation cumulate in a staging chamber during episodic expulsion of magma. In the central gabbro-peridotite sill, mineral compositions (Fo$_{olv} \sim 75-75$, Mg$\#_{opx} \approx 78-68$, An$_{plg} \approx 78-70$) and whole-rock data (MgO $\approx 22-27\%$, TiO$_2$ $\approx 0.4\%$) suggest that the parent magma was an olivine-saturated basalt containing 8-9 wt.% MgO. Whole-rock geochemical data further suggests that the parent magmas did not undergo any significant contamination (La/Sm$_N$ < 2, S/Se < 4,000). The Cu/Pd values of ultramafic units (> 10,000) suggest sulphide melt saturation was attained before their final emplacement in magma feeder conduits or staging chambers at relatively low $R$ factors (1,000-5,000). Downward decreasing concentrations of chalcophile elements in the drill cores suggests that sulphide melt percolated downward from the ultramafic cumulate units into the glomeroporphyritic gabbro footwall. We propose that the footwall ultramafic sills represent downward injections of olivine + sulphide melt from the overlying gabbro-peridotite sill, which mechanically concentrated high volumes of sulphide in narrow sills.
Keywords: Labrador Trough, magmatic ore deposit, sulphide, mineral exploration, Canada, sill complex
1. Introduction

The Labrador Trough in northern Québec (Fig. 1A) is under active exploration for magmatic Ni-Cu-PGE sulphide deposits. It extends for ~ 800 km from the southwestern margin of Ungava Bay to the Grenville Front, comprising thick packages of passive margin sediments, intruded by voluminous tholeiitic mafic-ultramafic lithologies of the Montagnais Sill Complex (MSC; Dimroth, 1978; Skulski et al., 1993). The MSC was emplaced contemporaneously with mafic-ultramafic rocks of the Cape Smith and Thompson Ni Belts (~ 1.88 Ga; Barager and Scoates, 1981; Scoates et al., 2017), which are host to the world-class Raglan and Thompson magmatic sulphide deposits, respectively. However, only sub-economic magmatic sulphide occurrences have so far been discovered in the Labrador Trough (e.g., Lac Retty, Clark, 1991; Hope’s Advance, Wares and Mungall, 1997).

The Huckleberry Cu-Ni-(PGE) prospect (55°46’N 66°56’W; Fig. 1B) is located ~ 100 km north of Schefferville and encompasses 158 claims over 76.6 km² (Fig. 1; Vaillancourt et al., 2016). The prospect represents a ~ 200-m-thick stack of glomeroporphyritic gabbro sills intruded in their centre by a ~ 200-m-thick differentiated gabbro-peridotite sill (Fig. 1C). Moreover, several < 30-m-thick ultramafic intrusions are hosted within the glomeroporphyritic gabbro footwall of the gabbro-peridotite sill. From 147 grab samples, 98 possess an average grade of 1% Cu, 0.2% Ni, and 0.72 g/t PGE\textsubscript{Pd+Pt} + Au, with peak values of 14% Cu, 1.2% Ni, and 17 g/t PGE\textsubscript{Pd+Pt} + Au. To date, over 5,000 m of diamond drilling (sixteen boreholes) has delineated four sulphide-bearing horizons, which are characterised in this contribution. We further examine the architecture and petrogenesis of the Huckleberry prospect to better understand the ore-forming processes operating in the Labrador Trough.

2. Regional setting
The Labrador Trough (or New Québec Orogen) is a NNW-SSE oriented fold-and-thrust belt, primarily composed of Archaean to Palaeoproterozoic volcanic and metasedimentary rocks (Hoffman, 1990; Henrique-Pinto et al., 2019). Pervasive westward imbricate thrusting occurred during oblique collision between the Superior and Southern Rae craton at 1.84 to 1.82 Ga. As a result, thrust zones are thought to have propagated to the base of the crust (Wares and Goutier, 1990; Wardle and Van Kranendonk, 1996). Metamorphic grade increases from west to east, peaking at greenschist to amphibolite facies in the Rachel-Laporte zone (Perreault and Hynes, 1990; Skulski et al., 1993).

The stratigraphy of the trough is characterised by two cycles of passive margin sediments (i.e., epicontinental to pelagic sediments) containing subordinate basaltic and calc-alkaline magmatic rocks and a third cycle of molasse-style deposits (Dimroth, 1978; Wardle et al., 2002; Clark and Wares, 2005). Basaltic and rhyolitic sills within Cycle 1 sediments were emplaced during 2169 ± 4 Ma and 2142 ± 4 Ma, respectively (Dressler and Krogh cited in Clark, 1984; Rohon, 1989; Skulski et al., 1993). The MSC was emplaced into Cycles 1 and 2 approximately 258 Ma later, at ~ 1884 ± 1.6 Ma (Findley et al., 1995; Machado et al., 1997). Aphyric and glomeroporphyritic basalts belonging to the Willbob (south) and Hellancourt (north) Formations were emplaced contemporaneously with the MSC (Rohon et al., 1993). The tectonomagmatic setting of the MSC remains poorly understood, with several hypotheses proposed, including: (1) dextral oblique extensions above an east-dipping subduction zone (Hoffman, 1990), (2) dextral transtension along the eastern margin of the Superior craton, resulting in the formation of pull-apart rift basins (Skulski et al., 1993), (3) extension in a continental back-arc (Corrigan et al., 2009; 2016; Van Rooyen et al., 2019), and (4) derivation from a deep-seated mantle plume (Ciborowski et al., 2017).

Previous researchers have identified three major sill types that comprise the MSC, these include; (i) aphyric (equigranular) gabbroic sills with stratiform gabbroic pegmatites, (ii)
glomeroporphyritic gabbro sills, and (iii) thick differentiated gabbro sills that sometimes host basal peridotitic cumulates (Clark and Wares, 2005 and references therein). To date, magmatic sulphide occurrences rich in PGE relative to base metals (S < 5 vol.%) are found exclusively in the northern parts of the Labrador Trough in sill type (i) (e.g., Paladin, Lac Lafortune, and Idefix). In contrast, sulphide occurrences rich in base metals relative to PGE (2 to 10 vol.% S) are found along the strike length of the Labrador Trough, in sill types (ii) and (iii) (e.g., Lac Retty, Hopes Advance, Lepage, Leslie, and Chrysler; Clark and Wares, 2005). These deposit types generally occur in close proximity to major thrust faults (< 5 km) and sulphidic sediments of the Menihek, Murdoch, and Baby Formations, suggesting assimilation of supra-crustal rock may have played a role in the formation of magmatic sulphide occurrences in the Labrador Trough (e.g., Chauvel et al., 1987; Rohon et al., 1993; Clark and Wares, 2005).

3. Geology of the Huckleberry Cu-Ni-(PGE) prospect

3.1. Historical exploration

There has been no previous exploration work conducted on the claims owned by Northern Shield Resources. The geological mapping works of E. Dimroth between 1964 and 1975 (synthesised in Dimroth, 1978) covers the Huckleberry prospect and the surrounding geology. In addition, the Ministère de l’énergie et des ressources naturelles du Québec have conducted regional geochemical (soil and lake bottom sediment; Maurice and Labbé, 2009) and geophysical (airborne magnetic and electromagnetic; Dion and Lefebvre, 1998; D’Amours and Intissar, 2013) surveys that encompass the Huckleberry prospect. In 1996, Totem Sciences conducted grab sampling and geophysical surveys at the Split Lake Showing that occurs a few kilometres south of Huckleberry. Samples of glomeroporphyritic gabbro
comprising disseminated sulphides returned grades of up to 0.38% Ni and 1.2% Cu (Scott and Mills, 1996).

The Huckleberry Cu-Ni-(PGE) prospect was discovered by Northern Shield Resources in 2014 following helicopter reconnaissance that identified numerous gossanous outcrops (Fig. A). Northern Shield Resources conducted several field reconnaissance surveys at the Huckleberry prospect between 2014 and 2018, which included a versatile time domain electromagnetic (VTEM™) geophysical survey and a sixteen-hole diamond drilling programme totalling >5,000 m of drill core. This work led to the identification of four sulphide-bearing horizons, which in order of increasing economic interest include: (i) globular sulphides at the base of the glomeroporphyritic gabbro (average grades of 0.36% Cu, 0.1% Ni, and 0.06 g/t PGE_{Pt+Pd} + Au over ~4 m), (ii) disseminated to net-textured sulphides in glomeroporphyritic gabbro (average grades of 0.36% Cu, 0.1% Ni, and 0.15 g/t PGE_{Pt+Pd} + Au over ~5-20 m), (iii) disseminated to net-textured sulphides in olivine cumulates at the base of the gabbro-peridotite sill (average grades of 0.29% Cu, 0.13% Ni, and 0.38 g/t PGE_{Pt+Pd} + Au over ~5-15 m), and (iv) net-textured sulphides in olivine cumulates within the glomeroporphyritic gabbro footwall to the central gabbro-peridotite sill (average grades of 0.28% Cu, 0.16% Ni, and 0.3 g/t PGE_{Pt+Pd} + Au over ~8-15 m). Detailed accounts of exploration work conducted by Northern Shield Resources are reported in Vaillancourt et al. (2016) and Vaillancourt and Murry (2017).

3.2. Local geology

The Huckleberry Cu-Ni-(PGE) prospect is located in the Hurst lithotectonic zone of Clark and Wares (2005; Fig. 1A). This zone is characterised by intercalated metapelites, banded iron formations, and pyroclastic rocks of the Attikamagen and Ferriman Groups, thrust over
the Howse zone along the Chassin Fault (Clark and Wares, 2005). The Menihek Formation occurs in the upper half of the Ferriman Group and is composed of sulphidic mudstones, pyroclastics, and basalts belonging to the Willbob Formation. The Menihek Formation is intruded by several aphyric and glomeroporphyritic gabbro sills, which are host to magmatic sulphides (Clark and Wares, 2005).

The strata exposed at the Huckleberry prospect are laterally continuous over the length of the property. They strike NNW-SSE and dip ~ 30-45° to the east (Fig. 1B-C). The interval of interest is a ~ 400-m-thick sill complex emplaced amongst metapelitic and volcaniclastic units of the Menihek Formation. The sill stack represents a ~ 200-m-thick stack of glomeroporphyritic gabbro sills, where individual sills are defined by sharp changes in size and population density of plagioclase glomerocrysts (Fig 2B-C). The stack of glomeroporphyritic gabbro sills are intruded in their centre by a ~ 200-m-thick differentiated gabbro-peridotite sill (Fig. 1C; Fig. 2D-G). Moreover, several lenses of ultramafic rock outcrop in the upper portion of the glomeroporphyritic gabbro sequence that stratigraphically underlies the gabbro-peridotite sill (Fig. 1B).

The gabbro-peridotite sill consists of olivine cumulates overlain by olivine gabbro, aphyric gabbro, titanomagnetite gabbro, and granophyre. This unit and the ultramafic lenses in the footwall glomeroporphyritic gabbro comprise variable abundances of assimilated plagioclase glomerocrysts, confirming that these units were emplaced after the glomeroporphyritic gabbros. In addition, to the east of the sill stack is an aphyric gabbro with no olivine cumulates that intrudes metapelitic rocks of the Menihek Formation, herein referred to as the hanging wall gabbro.

4. **Materials and Methods**
Grab samples were collected by Northern Shield geologists during annual field seasons between 2014 and 2018. Additional, grab and drill-core samples were collected by the author in the summer of 2018. Samples were prepared for petrographic analysis at Cardiff University (UK), using a Leica MZ12s microscope with a camera attachment.

All whole-rock \((n = 50)\) and assay \((n = 587)\) geochemical analyses were performed by ALS Minerals (Vancouver). Sample preparation was completed at ALS Minerals (Timmins) using the PREP-31 package. Lithophile major and trace elements were determined through ICP-AES and ICP-MS respectively, following four-acid digestion of fused beads (ALS codes ME-ICP06, ME-MS81, ME-MS42*, ME-4ACD81, and ME-ICP61a). Loss on ignition (LOI) was determined using the OA-GRA05 package. Sulphur and carbon concentrations were determined using a Leco sulphur analyser, whereby 0.1 g of homogenised sample is combusted at ~ 1350°C and total S and C are measured using a non-dispersive infrared sensor (ALS code ME-IR08). Palladium, Pt, and Au concentrations were determined by ICP-MS, following lead oxide fire assay to produce a precious metal bead (ALS codes FA-FUSPG4 and PGM-MS23). More information regarding analytical procedures can be found on the ALS Minerals website (www.alsgobal.com). The full dataset as well as standards and blanks are reported in Supplementary Material 1. The concentrations of PGE in whole-rock samples \((n = 25)\) were determined at LabMaTer (Université du Québec à Chicoutimi, Canada) using Ni-sulphide fire assay followed by Te coprecipitation and ICP-MS solution analysis (Savard et al. 2010). Standards, blanks, and analytical precision are reported in Supplementary Material 1.

The compositions of olivine \((n = 48)\), orthopyroxene \((n = 18)\), clinopyroxene \((n = 34)\) and plagioclase \((n = 69)\) were determined using a Zeiss Sigma HB Field Emission Gun Analytical Scanning Electron Microscope (SEM), equipped with two Oxford Instruments 150 mm² energy dispersive spectrometers at Cardiff University, United Kingdom (e.g.,
Mineral compositions were collected over four analytical sessions using an accelerating voltage of 20 kV, an acquisition livetime of 10 s, a process time of 3 s, a working distance of 8.9 mm and a spot size of 2 to 5 μm. A pure cobalt reference standard was used to optimise beam current drift and a suite of secondary standards from both ASTIMIX and Smithsonian were used to calibrate the EDS analysers on an hourly basis (Supplementary Material 2).

5. Results

5.1. Petrography

5.1.1. Metasedimentary and volcanic country rocks

The metasedimentary rocks of the Menihek Formation consist of well-laminated greyish metapelitic and meta-arenitic rocks (Fig. 3A), interdigitated with crystal and lapilli tuffs. Well-laminated graphitic and sulphidic argillites occur in the footwall and hanging wall of the sill complex, comprising up to 50 vol.% exhalative sulphide in the form of: (i) < 3-cm-thick irregular bands or patches of pyrrhotite (Fig. 3B), (ii) mm- to cm-scale laminations of pyrrhotite and pyrite (Fig. 3C), (iii) pyrite-bearing quartz veins/lenses (Fig. 3D), and (iv) crackle-textured pyrrhotite and pyrite (Fig. 3E-F). Massive basalts occur along the eastern margin of the claims. The rocks are predominantly aphanitic, yet occasionally display subophitic textures. In some cases, chilled margins are visible along their upper contact, suggesting some of the rocks represent sub-volcanic intrusions rather than extrusive flows.

5.1.2. Hanging wall gabbro sill

The ~ 120-m-thick hanging wall aphyric gabbro is fine- to medium-grained and consists of roughly equal proportions of partially to completely uralitised clinopyroxene and partially to completely saussuritized plagioclase. Accessory phases include titanite, actinolite, tremolite,
quartz, apatite, and Fe-Ti oxides. There is no evidence for deformation in this unit. Sparsely
disseminated sulphides are observed this unit and in some case, globular and disseminated
sulphides occur at the base of the sill.

5.1.3. Glomeroporphyritic gabbro sills

The glomeroporphyritic gabbro sills represent a fine- to medium-grained gabbroic
groundmass that encloses variable abundances of off-white, saussuritized plagioclase
glomerocrysts than range in diameter from 1 to 10 cm (Fig 4A-D). The relative abundance of
plagioclase glomerocrysts has led to the sub-division of this unit into the gabbroic
glomeroporphyritic unit (GGU; > 20 vol.% plagioclase glomerocrysts) and the pyroxenitic
glomeroporphyritic unit (PGU; < 20 vol.% plagioclase glomerocrysts). In some cases,
plagioclase glomerocrysts can comprise > 80 vol.% of the rock.

The PGU occurs at the base of the sill complex and comprises a groundmass that
consists of roughly equal proportions of uralitised clinopyroxene and saussuritized
plagioclase, with accessory titanite, apatite, and Fe-Ti oxides (Fig 4E). The groundmass of
the GGU is similar to that of the PGU (Fig. 4F). The plagioclase glomerocrysts are typically
saussuritized from the inside outward and those in the GGU are generally more altered than
those in the PGU.

5.1.4. Differentiated gabbro-peridotite sill

The ~ 200-m-thick gabbro-peridotite sill consists of wehrlitic cumulates (~ 20 m), olivine
gabbro (~ 80 to 90 m), aphyric gabbro (~ 80 to 100 m), titanomagnetite gabbro (~ 10 m), and
granophyre (< 5 m). The wehrlite cumulate (Fig. 5Ai-ii) is fine-grained and comprises
partially serpentinised olivine chadacrysts (< 1 mm in diameter and ~ 60-70 vol.%)
embedded in partially to completely uralitised clinopyroxene (~ 20-30 vol.%; Fig. 5Aiii-iv)
and seldom rimmed by orthopyroxene (< 5 vol.%). Accessory phases include cumulus
plagioclase, ilmenite with titanomagnetite exsolution lamellae, vein-hosted magnetite, and apatite. This unit can host up to 30 vol.% partially resorbed plagioclase glomerocrysts that are interpreted to have been assimilated from the GGU footwall. The glomerocrysts are often greenish, well-rounded and outlined by a very fine-grained blackish rim of amphibole that can be up to 1 cm thick.

The modal abundance of olivine decreases with height, grading from wehrlite to fine- to medium-grained olivine gabbro (Fig. 5Bi). The latter consists of cumulus olivine (0.5 to 3 mm in diameter at ~ 10-15 vol.%), which sometimes form sintered clusters with ~ 120° dihedral angles (Fig. 5Bii), subhedral cumulus plagioclase (0.5 to 2 mm in length at ~ 50-60 vol.%), clinopyroxene oikocrysts (~ 10-15 vol.%) and orthopyroxene rims on olivine (< 5 vol.; Fig. 5Biii), with an accessory phase assemblage comparable to that of the olivine cumulates (Fig. 5B).

The fine- to medium-grained aphyric gabbro (Fig. 5Ci-ii) resembles the hanging wall gabbro, in that is comprises roughly equal proportions of uralitised interstitial to sub-ophitic clinopyroxene (Fig. 5Ciii-iv) and saussuritized cumulus and intercumulus plagioclase (0.5-4 mm) with traces of orthopyroxene (< 5 vol.%; Fig. 5C). Overlying this unit is the fine- to medium-grained titanomagnetite gabbro (Fig. 5Di-ii) that comprises ~ 50 vol.% plagioclase, ~ 35 vol.% clinopyroxene (Fig. 5Diii), and up to 15 vol.% titanomagnetite-ilmenite intergrowths (< 2 mm in diameter) with magnetite exsolution lamellae (Fig. 5Div). The top of the sill consists of a pegmatic granophyric gabbro (Fig. 5Ei-ii) that comprises bladed to radial hornblende (0.5 to 4 cm in length at ~ 40 vol.%), acicular actinolite and tremolite (~ 25 vol.%), quartz-feldspar granophyre (~ 15 vol.%), titanomagnetite with ilmenite exsolution lamellae (~ 15 vol.%), leucoxene and interstitial apatite (~ 1 vol.%), with accessory mica, zircon, and rutile (Fig. 5Eiii-iv).
5.1.5. Footwall ultramafic sills

The footwall ultramafic sills (< 30 m in true thickness; Fig. 5Fi-ii) are thought to represent an anastomosing network in the glomeroporphyritic gabbro footwall. This unit is comparable to the basal olivine cumulates in that it comprises partially to completely serpentinised olivine (< 1 mm in diameter at ~ 60-70 vol.%), embedded either in oikocrystic orthopyroxene (< 10 vol.%) or clinopyroxene (~ 5-25 vol.; Fig. 5Fiii), with accessory plagioclase, titanite, and apatite. This unit can host up to 50 vol.% resorbed plagioclase glomerocrysts (0.5-20 cm in diameter), and certain intervals are classified as ultramafic-glomeroporphyritic gabbro mixed zones (Fig. 5Fiv).

5.2. Sulphide textures and mineralogy

5.2.1. Globular sulphides in the PGU

Globular sulphides (< 3 cm in diameter) with satellite disseminated sulphides occur in the PGU, adjacent to the metasedimentary footwall (Fig. 6Ai-ii). Typically, the globules comprise a lower margin of pyrrhotite (~ 60-70 vol.%) that hosts fine pentlandite exsolution lamellae and an upper margin of chalcopyrite (~ 20-30 vol.%) that seldom hosts inclusions of sphalerite (Fig. 6Ai-iv). Granular pentlandite (~ 10-15 vol.%) occurs at the margins of pyrrhotite or at the contacts between pyrrhotite and chalcopyrite. The globules are often lined with dark rims that are thickest along their upper margin and comprise amphiboles and quartz. Few fine-grained sulpharsenides occur at the margins of globule-hosted pyrrhotite or amongst the satellite sulphide disseminations. The disseminations consist predominantly of pyrrhotite and chalcopyrite and are spatially associated with subhedral ilmenite with titanomagnetite exsolution lamellae.
5.2.2. Disseminated and net-textured sulphides in the glomeroporphyritic gabbro

Disseminated and net-textured sulphides occur in glomeroporphyritic gabbro that underlies the gabbro-peridotite sill and its footwall ultramafic sills. Sulphides commonly mould around plagioclase glomerocrysts (Fig. 6Bi) and are characterised by pyrrhotite (~ 20-30 vol.%) hosting pentlandite exsolution lamellae, chalcopyrite (~ 50-60 vol.%), sphalerite (~ 2-4 vol.%), and granular pentlandite (~ 10-15 vol.; Fig. 6Bii-iii). The margins of sulphides are often lined with actinolite and tremolite. In some cases, veins of chalcopyrite (with accessory pyrrhotite and pentlandite) are observed cross-cutting plagioclase glomerocrysts.

5.2.3. Disseminated and net-textured sulphide at the base of the gabbro-peridotite sill

Sulphides are sparsely disseminated throughout the gabbro-peridotite sill and are most concentrated amongst the basal olivine cumulates. The sulphides occur interstitially to cumulus olivine and are also observed moulding around assimilated plagioclase glomerocrysts (Fig. 6Ci). The sulphides comprise variable proportions of pyrrhotite (~ 20-70 vol.%), chalcopyrite (~ 30-50 vol.%) with cubanite exsolution lamellae (~ 0-15 vol.%), and granular pentlandite (~ 5-20 vol.; Fig. 6Cii). No pentlandite exsolution lamellae is present in pyrrhotite. Moreover, cubanite exsolution lamellae often comprise pyrrhotite exsolution lamellae. In some samples, chalcopyrite and cubanite occur along fractures in granular pentlandite. There are several lines of evidence suggesting alteration of the primary sulphides: (i) lining of sulphide by amphiboles, (ii) patches of serrated sulphides and amphiboles (Fig. 6Ciii), and (iii) the replacement of pyrrhotite by magnetite.
5.2.4. Net-textured sulphide in the footwall ultramafic sills

The nature of sulphides in this unit is comparable to those at the base of the gabbro-peridotite sill in that sulphides occur interstitially to cumulus olivine and often mould around assimilated plagioclase glomerocrysts (Fig. 6Di-ii). However, the sulphide mineralogy differs somewhat, whereby the assemblage is dominated by pyrrhotite with no pentlandite exsolution lamellae (~ 10-80 vol.%), cubanite (~ 15-25 vol.% with chalcopyrite exsolution lamellae (~ 2-10 vol.%), and granular pentlandite (~ 5-15 vol.% with boxwork mackinawite exsolution lamellae that can occupy up to 30% of the pentlandite (Fig. 6Diii). Mackinawite-bearing pentlandite is consistently lined by cubanite that hosts angular fragments of pentlandite.

Pyrrhotite adjacent to this cubanite hosts worm-like troilite exsolution lamellae. The sulphides display the same lines of evidence for alteration as that stated above.

5.3. Mineral chemistry

The compositions of olivine, orthopyroxene, clinopyroxene, and plagioclase are summarised in Table 1 and the full dataset is reported in Supplementary Material 1. Relatively widespread alteration of each of these phases prevented a detailed mineral chemistry study.

5.3.1. Olivine

Olivine in the basal olivine cumulates ranges from Fo 77.1 to 73.0 mol.% (average 75.7 ± 0.4 mol.%) and 2,848 to 1,886 ppm Ni (average 2,375 ± 65 ppm). The composition of olivine in the olivine gabbro is less magnesian (Fo 73.9 to 65.7 mol.%; average 71.3 ± 1.7 mol.%) and less nickeliferous (2,396 to 1,699 ppm; average 2,090 ± 151 ppm). Olivine in the footwall olivine cumulates has the lowest Fo content (69.5 to 68.0 mol.%; average 68.4 ± 0.6 mol.%), yet the highest Ni concentrations (2,711 to 2,530 ppm; average 2,592 ± 63 ppm). There is no
obvious correlation between Fo and Ni in olivine or between Fo and An content of plagioclase in any unit.

5.3.2. Orthopyroxene

No compositional zonation is apparent in analysed orthopyroxene. In the basal olivine cumulates, orthopyroxene records the highest measured Mg#, ranging from 79.2 to 76.5 mol.% (average 78.5 ± 1.1 mol.%), with a Cr range of 1,437 to 1,056 (average 1,267 ± 146 ppm), and a Ni range of 1,269 to 741 (average 979 ± 239 ppm). Orthopyroxene in the olivine gabbro is generally more evolved with an Mg# range of 75.4 to 68.4 mol.% (average 73.1 ± 2.6 mol.%), a Cr range of 2,354 to 299 ppm (average 1,382 ± 882 ppm), and a Ni range of 1,121 to 589 ppm (average 797 ± 168 ppm). In the footwall olivine cumulates, Mg# of orthopyroxene ranges from 78.4 to 73.0 mol.% (average 75.5 ± 2.1 mol.%), with a Cr range of 1,745 to 78 ppm (average 659 ± 636 ppm), and a Ni range of 1,280 to 822 ppm (average 1,102 ± 177 ppm).

5.3.3. Clinopyroxene

No compositional zonation is apparent in analysed clinopyroxene. One oikocryst was analysed in the basal olivine cumulate (sample 06B), which is characterised by a high Mg# (79.9 mol.%), Cr (4,392 ppm) and Ni (786 ppm) concentration. In the olivine gabbro, clinopyroxene Mg# ranges from 83.2 to 73.6 mol.% (average 77.3 ± 0.5 mol.%), with variable Cr concentrations ranging from 4,843 to 827 ppm (average 3,545 ± 1,083 ppm) and Ni concentrations ranging from 692 to 146 ppm (average 386 ± 162 ppm). Clinopyroxene through the gabbro-peridotite sill, ranges in Mg# from 81.2 to 79.7 mol.% in the aphyric gabbro (average 80.7 ± 0.6 mol.%), to 61.0 to 58.5 mol.% in the titanomagnetite gabbro.
(average 60.0 ± 1.0 mol.%). The Cr and Ni concentrations overlap between clinopyroxene hosted in the olivine gabbro and aphyric gabbro.

Interstitial clinopyroxene in the PGU is characterised by an Mg\# range of 76.2 to 55.8 mol.% (average 69.8 ± 7.2 mol.%), a Cr range of 1,740 to 258 ppm (average 767 ± 684 ppm) and a Ni range of 540 to 324 ppm (average 427 ± 89 ppm). Clinopyroxene in the overlying glomeroporphyritic gabbro possess the same range of Mg\# content, Cr and Ni concentrations. The Mg\# and Cr contents show a positive correlation (R^2 = 0.73) across the dataset and Mg\# generally increase with increasing plagioclase An.

5.3.4. Plagioclase

All analysed matrix plagioclase showed oscillatory compositional zoning, with a broad trend of decreasing An content towards the rims of grains. Plagioclase becomes more evolved in composition upward through the gabbro-peridotite sill, in that core domains of grains have An from 77.3 to 71.5 mol.% (average 78.8 ± 1.8 mol.%) in the olivine gabbro, from 78.0 to 60.3 mol.% (average 69.4 ± 7.7 mol.%) in the aphyric gabbro, and from 57.4 to 52.9 mol.% (average 55.2 ± 2.2 mol.%) in the titanomagnetite gabbro. The An content of rims of grains are generally 5-10 mol.% less than in the corresponding core.

Matrix-hosted plagioclase in the PGU is less evolved that that in the gabbro-peridotite sill, in that core domains have An from 70.9 to 60.4 mol.% (average 65.6 ± 4.4 mol.%) and rims range from 58.1 to 50.2 mol.% (average 55.3 ± 2.9 mol.%). In the GGU, matrix plagioclase becomes move evolved in that cores range in An from 64.9 to 9.8 mol.% (average 46.6 ± 19.9 mol.%) and rims range from 64.1 to 14.7 mol.% (average 43.7 ± 17.1 mol.%). At the top of the GGU, no oscillatory zoning is detectable in matrix-hosted plagioclase.

Glomerocryst-hosted plagioclase show oscillatory zoning and their compositions overlap
with that of matrix-hosted plagioclase, in that An ranges from 67.5 to 55.4 mol.% (average 59.3 ± 3.2 mol.%). Saussuritization prevented analysis of glomerocryst cores.

5.4. Whole-rock geochemistry

5.4.1. Lithophile elements

Representative whole-rock analyses are reported in Table 2 and the full dataset can be found in Supplementary Material 2. The glomeroporphyritic gabbros largely plot along the clinopyroxene-plagioclase tieline in Fenner diagrams (Fig. 7A-D). The olivine cumulates can broadly be modelled by assuming that they consist of variable proportions of olivine, orthopyroxene, and assimilated plagioclase glomerocrysts (Fig. 7A-D). Olivine gabbro and aphyric gabbro are characterised by variable proportions of cumulus plagioclase, olivine, clinopyroxene, and orthopyroxene.

Compared with the PGU, the GGUs contain a greater relative proportion of plagioclase resulting in higher Al₂O₃, CaO, Na₂O, K₂O, and Sr, lower FeO, TiO₂, and Sc, and broadly similar Cr/V, MnO, and P₂O₅ contents. The enrichment in TiO₂ in the PGU corresponds to an increase in modal titanite and Fe-Ti oxide (Fig. 7E). Some of the GGU samples show a pronounced enrichment in Ni (< 4,200 ppm) and Cu (< 16,000 ppm) over a narrow interval of MgO content (~ 3 to 5 wt.%). This coincides with an increase in sulphur content.

In the olivine gabbro and olivine cumulates, Al₂O₃, CaO, Na₂O, K₂O, and Sr generally decrease with increasing MgO content, whereas TiO₂, MnO, P₂O₅, and Sc remain constant and FeO₅, Cr/V, Ni, and Co increase (Fig. 7F-G; Tab. 2). These units also show a relative enrichment in plagioclase constituents (i.e., Na, Ca, K, Al, and Sr) and progressive depletion in incompatible elements (i.e., Ti, P, Sc, Nb < 2 ppm, Zr < 20 ppm, and Hf < 2...
ppm) with decreasing MgO content. In the basal olivine cumulates, Ni concentration gradually decreases with falling MgO, which coincides with low sulphur (< 0.5 wt.%) and Cu content (< 500 ppm). However, in the footwall olivine cumulates and olivine gabbro, Ni and Cu range from 1,000 to 4,000 ppm and 400 to 14,000 ppm, respectively (Fig. 7G-H).

In the upper portions of the gabbro-peridotite sill, SiO$_2$, FeOt, Na$_2$O, K$_2$O, TiO$_2$, MnO, P$_2$O$_5$, and incompatible trace elements (e.g., Zr, Nb, Sr) increase with decreasing MgO and Al$_2$O$_3$, CaO, and Cr/V decrease with decreasing MgO (Fig. 7A-F). The hanging wall gabbro samples show good compositional overlap with the aphyric gabbro samples of the gabbro-peridotite sill.

The metapelitic and meta-arenitic units of Menihek Formation are characterised by pronounced enrichment in LILEs and HFSEs (Th/Yb$_N$ > 10), as well as LREE (La/Sm$_N$ > 3; La/Yb$_N$ > 7) relative to primitive mantle (Fig. 8A). In contrast, the trace element concentrations of massive basalts are generally 2-10x that of primitive mantle and display relatively flat REE profiles.

In the glomeroporphyritic gabbros, trace element contents (including REE) are generally 2-10x that of primitive mantle (Fig. 8B). Both the GGUs and PGU are characterised by flat trace element profiles (Nb/Nb$^*$ = 1.3-2.0; Th/Yb$_N$ = 0.57-0.92; La/Yb$_N$ = 0.83-1.29). The PGU generally shows slightly negative Eu/Eu$^*$ [Eu$_N$ / (Sm$_N$ * Gd$_N$)$^{0.5}$] values of ~ 0.82, whereas the GGUs generally shows positive values (0.97-1.33).

The aphyric and titanomagnetite gabbros of the upper gabbro-peridotite sill have more fractionated primitive mantle normalised patterns than the underlying olivine gabbro (Fig. 8C-E). Their patterns broadly correlate with that of the glomeroporphyritic gabbros (Nb/Nb$^*$ = 1.53-2.05; Th/Yb$_N$ = 0.59-0.97). These lithotypes generally show flat REE profiles (La/Yb$_N$...
patterns are comparable to that of the aphyric gabbro.

The basal olivine cumulates are generally more enriched in incompatible trace elements (~ 2x) than the footwall olivine cumulates (~ 1-1.5x), relative to primitive mantle (Fig. 8F). However, both lithotypes are characterised by flat trace element patterns (Nb/Nb$^*_N$ = 1.03 to 1.89; Th/Yb$_N$ = 0.48-0.77), with positive Rb and Ti anomalies and slight to pronounced negative Th, Nb, and Sr anomalies. Furthermore both are characterised by relatively flat REE profiles (La/Yb$_N$ = 0.72-1.39) and slight negative Eu/Eu$^*$ values (0.41-0.89).

5.4.2. Correction for background Ni contents in olivine-bearing rocks.

Due to the compatibility of Ni in olivine, corrections must be applied to the whole-rock Ni contents before deriving Ni tenors for olivine-bearing rocks (e.g., Kerr, 2001). To determine the background Ni content of olivine-bearing rocks at Huckleberry (i.e., whole-rock Ni corresponding only to silicate minerals), we follow the procedure detailed in Barnes et al., (2011) for the Santa Rita deposit. In Figure 7G, it is shown that Ni positively correlates with whole-rock sulphide in the olivine-bearing rocks. It should be noted that samples with < 0.5 wt.% sulphur and < 200 ppm Cu are exempt for the correction because uncertainty can exceed 50% at low sulphur concentrations (see Barnes et al., 2011).

The filtered samples were grouped into (i) olivine cumulate rocks, (ii) gabbroic rocks, and (iii) glomeroporphyritic gabbroic rocks (Fig. 9A). Through linear regression analysis, linear expressions for Ni hosted in silicate were determined as a function of MgO content and rock type, using the equations:
Olivine cumulate rocks→Ni(sil) = 43.661 × MgO – 180.12
Gabbroic rocks→Ni(sil) = 40.587 × MgO – 207.93
Glomeroporphyritic gabbroic rocks→Ni(sil) = 22.168 × MgO – 13.027

Through subtracting Ni(sil) from Ni(whole-rock), Ni(sul) can be determined (Fig. 9B-C).
This correction results in a significant reduction in the Ni content of nearly all the footwall
olivine cumulates and olivine gabbro samples, as well as few basal olivine cumulate samples.
Nickel tenor was calculated from Ni(whole-rock) minus Ni(sil) (Tabs. 2 and 3). To test the
degree of uncertainty, the difference between calculated and measured Ni contents is plotted
in Figure 9D. The difference ranges from -86.1 (5th percentile) to 72.5 (95th percentile), where
the uncertainties peak at zero error. Samples with < 500 ppm Ni generally show larger
variation that those with > 500 ppm Ni, suggesting that the correction is more accurate for
olivine-poor samples than olivine-rich samples, in-keeping with observations made by Barnes

5.4.3. Chalcophile elements

Representative chalcophile element whole-rock analyses are reported in Table 2 and the full
dataset can be found in Supplementary Material 2. All samples analysed for a full suite of
PGE are given in Table 3. Sulphide-bearing glomeroporphyritic gabbros generally have
higher Cu concentrations (< 14,000 ppm Cu; Ni/Cu < 0.5) relative to sulphide-bearing
gabbro-peridotite samples (< 10,000 ppm Cu; Ni/Cu > 0.5; Fig. 10A). In all samples, Cu and
PGE_{Pt+Pd} + Au increase with increasing sulphur (Fig. 10B-C). All lithotypes that host
disseminated and net-textured sulphides are characterised by high Cu (Cu/S > 4,000) and
PGE_{Pt+Pd} + Au (PGE/S > 400; Fig. 10D). Globular sulphides in the PGU are characterised by
lower chalcophile metal concentrations (Cu/S < 1,000; PGE/S < 100). All sulphide-bearing
horizons show Pd/Pt values of ~2.5 to 3.5 (R^2 = 0.76), which becomes progressively more
variable at high Pd (> 0.3 ppm) and Pt (> 0.1 ppm) concentrations (Fig. 10E). Basal olivine
cumulate samples have a more variable Pd/Pt values (~ 3.76 ± 1.32) than the footwall olivine
cumulates (~ 3.62 ± 0.42). Ratios of S/Se broadly decreases with increasing Pt+Pd tenor,
whereby the olivine cumulates have the lowest S/Se (3,000-1,000) and highest Pt+Pd tenor
(10-50 ppm; Fig. 10F). The metasediments range in S/Se from ~ 2,000 to 10,000.

In Figure 11, whole-rock PGE concentrations from Lac Bleu (Clark, 1989; 1991) and
Hope’s Advance (Mungall, 2002) have been added for comparison. The PGE concentrations
from all localities generally show good overlap, yet Ru concentrations at Lac Bleu and
Hope’s Advance are typically higher that those at Huckleberry. In all Huckleberry samples,
Ir, Os, Ru, and Rh show good positive correlation with each other (R^2 > 0.95; Fig. 11A-C).
Although the concentrations of Pt, Pd, and Au appear to increase with increasing Ir, these
elements are characterised by low R^2 values (< 0.5; Fig. 11D-F). The samples have Pd/Ir
values ranging from 50 to 500.

Figure 12 displays chalcophile multi-element profiles for disseminated, net-textured,
and globular sulphides at Huckleberry, together with profiles from Lac Bleu (Clark and
Wares, 2005) and Raglan of the Cape Smith Belt (Barnes and Lightfoot, 2005). An ex situ
glacial erratic boulder hosting massive Cu-rich sulphide mineralisation (Pd/Ir > 10,000)
found at Huckleberry has been overlain as an example of hydrothermally precipitated
sulphide in the Labrador Trough. All samples with > 0.5 wt.% S have been recalculated to
100% sulphide via the mass balance equations of Naldrett et al. (2000) and are reported in
Table 3.

All Huckleberry patterns are relatively flat Ni and IPGE patterns (Ni/Ir_N ~ 1.44) at ~
10 to 50x that of primitive mantle. Rock units with disseminated to net-textured sulphides are
relatively enriched in Rh, Pt, and Pd (> 100x that of primitive mantle), whereas globular
sulphides of the PGU are generally less enriched in all PGE. All samples show a pronounced negative anomaly in Au and are enriched in Cu by > 1,000x that of primitive mantle. The Huckleberry sulphides have higher PGE contents than Lac Bleu. Compared to Raglan disseminated sulfides, the Huckleberry patterns have similar PPGE levels, yet lower Ni and IPGE concentrations.

5.4.4. Vertical geochemical variations in the ore-bearing horizons

Borehole 17HK-12 intersects the entire Huckleberry sill stack and has been used to characterise vertical variations in geochemistry (Fig. 13). It should be noted that similar trends are observed in other drill cores from the property (Supplementary Figure 2). The metasedimentary footwall is intersected at ~ 680 m, reflected by a sharp drop in MgO to < 2 wt.% and Ni to < 50 ppm. The PGU (~ 680 to 650 m) displays an upward increase in MgO and Cr/V and a decrease in TiO₂ and Zr. It comprises variable sulphur (0 to 0.6 wt.%) and Cu contents (20 to 1,000 ppm), which reflects the presence of globular sulphides. A thin anorthositic layer (~ 2 m at 660 m depth) marks a sharp decrease in MgO from ~ 10 to 3 wt.%. Upward through the glomeroporphyritic gabbros (~ 650 to 510 m), there is a broad decrease in MgO, TiO₂, and Zr and an increase in Cr/V. The concentration of chalcophile metals remains constant throughout this unit except in the ~ 20 m that underlies ultramafic cumulates. In these intervals, MgO, S, Ni, Cu, PGE, and Pd/Pt increase upward, whereas Cu/Pd decreases upward towards the ultramafic lithologies. The footwall olivine cumulates show pronounced MgO (< 26 wt.%), S (< 2 wt.%), Ni (< 2,000), Cu (< 4,000 ppm), and PGE (< 500 ppb) enrichments relative to the surrounding glomeroporphyritic gabbros. Moreover, Cu/Pd values (~ 10,000) are generally lower than the surrounding glomeroporphyritic gabbros, whereas Pd/Pt values (~ 3.5) are generally higher.
The basal olivine cumulate shows pronounced increases in MgO (< 30 wt.%), S (< 2 wt.%), Ni (< 2,000 ppm), and PGE (< 500 ppb) concentrations. The Cu/Pd values are generally lower than the footwall olivine cumulates (100 to 10,000), whereas the Pd/Pt values are generally higher (> 4). Upward through the olivine gabbro and aphyric gabbro, MgO and Ni decrease, TiO$_2$ and Zr increase, Cr/V initially increases and then decreases, and chalcophile metals remain constant. The upper titanomagnetite and granophyric gabbro are characterised by low MgO (~ 4 wt.%), Cr/V (< 0.5), and Ni (~ 20 ppm) and high TiO$_2$ (> 2 wt.%) and Zr (> 50 ppm).

The upper glomeroporphyritic gabbro displays much the same composition as the lower unit, except that there are no anomalous sulphur and chalcophile metal concentrations. The metasediments at the top of the borehole are variably enriched in S (~ 0.5 to 4.5 wt.%) and incompatible elements (i.e., Zr > 100 ppm). The hanging wall gabbro sill (~ 95 to 60 m) is marked by an increase in MgO (8 to 11 wt.%), where it displays subtle increases in chalcophile metal concentrations (Ni < 400 ppm; Cu < 200 ppm; PGE$_{Pb+Pd} +$ Au < 60 ppb) relative to the metasedimentary units.

6. Discussion

6.1. Composition and fractionation of the parent magmas

The composition of the parent magma is often estimated using chilled margins or co-magmatic basaltic rocks. Due to the lack of suitable chilled margins amongst the studied rocks, co-magmatic basaltic rocks provide the best estimate of the composition of magmas parental to the Huckleberry sill complex.
The composition of cumulus olivine can be used to determine the Mg# of the parent magma through the method of Chai and Naldrett (1992), by way of the Mg-Fe distribution coefficient between olivine and liquid (Roeder and Emslie, 1970), given as:

\[
K_D = \frac{(FeO/MgO)_{olv}}{(FeO/MgO)_{liq}} = 0.3 \pm 0.03
\]

The most forsteritic olivine (Fo\(_{77}\)) analysed at Huckleberry is consistent with a parent magma having 5.2 wt.% MgO and 8.8 wt.% FeOt, which is more evolved than the local basaltic units (~ 6-10 wt.% MgO; Fig. 14). However, Rohon (1989) found that the most forsteritic olivine from the neighbouring Lac Retty occurrence had a composition of Fo\(_{82}\), which is consistent with a parent magma with 8.7 wt.% MgO and 9.8 wt.% FeO; in keeping with the composition of Hellancourt basalts reported by Ciborowski et al. (2017).

Cumulus olivine can become less forsteritic through re-equilibration with trapped intercumulus liquid (Barnes, 1986). Although alteration precludes estimation of the volume of trapped liquid using whole-rock geochemistry, a rudimentary estimation can be made based on the relative proportions of intercumulus phases. If one assumes intercumulus clinopyroxene in the ultramafic cumulate rocks proportionally represents the initial trapped liquid volume (~ 4-18 vol.%), Fo\(_{olv}\) could be reduced by up to ~ 6 mol.% Fo (Barnes, 1986). The implication being that the most forsteritic olivine at Huckleberry could have initially been ~ 82-80 mol.%, consistent with the measurements of Rohon (1989).

Moreover, the composition of olivine can be modified though interaction with sulphide melt (e.g., Brenan, 2003; Li and Naldrett, 1999), via the Ni-Fe exchange reaction:

\[
NiO_{olv} + FeS_{sul} = NiS_{sul} + FeO_{olv}
\]

The exchange coefficient for this reaction is given as:
This reaction produces a negative relationship between mol.% Fo and Ni in olivine (e.g., Li et al., 2004). Barnes et al. (2013) demonstrated that the $K_D$ of olivine-sulphide pairs is composition dependent and so the $K_D$ will change at different $R$ factors. The iterative method of Barnes et al. (2013) for calculating $K_D$ in olivine-sulphide-liquid systems first calculates the composition of olivine equilibrated with a given parent magma, while keeping the composition of sulphide melt constant. Second, the equilibrium constant of sulphide melt is calculated, whilst keeping the olivine and silicate melt compositions constant. Olivine compositions are calculated with each step using the aforementioned method of Roeder and Emslie (1970), which has been modified by Herzberg and O’Hara (2002) to give the following equation

$$K_D = \frac{(NiS/FeS)^{sil}}{(NiO/FeO)^{oliv}}$$

At an $R$ factor of 5,000 and an initial sulphide melt Ni composition of 6 wt.%, the equilibrated olivine compositions are Fo79, consistent with those measured in this study and in Rohon (1989) and the calculated $K_D$ is 12.6. Using the method detailed in Li and Naldrett (1999), the composition of olivine equilibrated with a sulphide melt comprising 6 wt.% Ni at a $K_D$ of 12.6 shows good overlap with olivine measured in this study. Therefore, it is
plausible that the high Ni concentrations in olivine measured in this study, reflects interaction with sulphide melt comprising > 5 wt.% Ni.

6.2. A comment on magma source and tectonic setting

Basaltic and gabbroic rocks of the MSC are characterised by flat REE patterns and Nd isotopic compositions analogous to modern transitional mid-ocean ridge basalts (*e.g.*, Rohon et al., 1993; Skulski et al., 1993). Rohon (1989) reported arc-like compositions of basaltic rocks in the MSC and field observations reported in Corrigan et al. (2016) were consistent with a continental back-arc tectonic setting. Back-arc basalts are generally depleted in Ni compared to continental flood basalts, perhaps due to olivine fractionation during ascent (*e.g.*, Wilson 1989; Maier et al., 1998). Olivine fractionation at the base of the lower crust has been proposed to explain the petrogenesis of the glomeroporphyritic gabbros (Skulski et al., 1993) and the paucity in Ni-rich magmatic sulphide showings in the Labrador Trough (Smith et al., 2019).

Geochemical modelling shows that local basaltic rocks are saturated in forsteritic olivine (Fo82), corresponding to a parent magma with 8 to 10 wt.% MgO (this study and Ciborowski et al., 2017). Ciborowski et al. (2017) used PRIMELT3 software (Herzberg and Asimow, 2015) to calculate primary magma compositions and mantle potential temperatures ($T_p$) for the Hellancourt basalts and concluded that the primary magmas derived from > 30% partial melting of mantle peridotite with $T_p$ values exceeding that of ambient mantle at ~ 1.8 Ga. This study proposed that the mantle temperature was raised by the presence of a channelised mantle plume that became dismembered as it impinged along the base of the Superior craton. Ciborowski et al. (2017) further proposed that the compositional range of the Hellancourt
basalt was best replicated by fractional crystallisation at low pressure (< 2 kbar) in the
presence of a small amount of water (< 0.5 wt.%).

6.3. Crustal contamination

The formation of most magmatic sulphide deposits is believed to be related to addition of
external sulfur to the magma (Ripley & Li, 2013). The country rocks to the Huckleberry sill
complex are locally sulphide-rich (~ 5-50 vol.%; Figs. 3 and 10). Thus, the sulphide globules
at the base of the glomeroporphyritic gabbro sill stack could have formed via contamination.
However, none of the mafic-ultramafic rocks hosting the bulk of the sulphide mineralisation
show pronounced La/Sm$_N$, Th/Yb$_N$, La/Nb$_N$, or S/Se values expected to result from
significant crustal contamination (Tab. 2). In addition, the rocks do not appear to come into
direct contact with the country rocks and no sedimentary xenoliths have been identified. This
could mean that the sulphides did not segregate in response to contamination and addition of
external S, but instead formed through fractionation, or that the compositional effects of
contamination and addition of external S were eradicated by high $R$ factors, e.g., during
entrainment of the sulfides after their initial formation up-stream or in a magma feeder
conduit or staging chamber (Lesher and Burnham 2001). The latter model is consistent with
the elevated Cu/Pd ratios of the sulfides, indicating that the magmas equilibrated with
sulfides prior to final emplacement.

A PELE (Boudreau, 1999) fractional crystallisation simulation was conducted to
assess the timing of SCSS in a magma with a composition of the Hellancourt basalt with 200
ppm S (Tab. 4). Under the conditions outlined by Ciborowski et al. (2017; 1 kbar and 0.5
wt.% H$_2$O), sulphide melt segregates after Fe-Ti oxide saturation at ~ 75% crystallisation,
inconsistent with the presence of sulphides at the base of the gabbro-peridotite sill (Tab. 5). A
PELE assimilation-fractional crystallisation (AFC) simulation was conducted to test the effect of small degrees of crustal contamination on the SCSS. The Menihek Formation was primed at 200°C and 1 g was added as solid minerals per step to 100 g of Hellancourt basaltic magma. The Menihek assimilant has a modest S concentration of ~ 0.5 wt.% in these models (Tabs. 4 and 5). Sulphur saturation is achieved after ~ 35% crystallisation, prior to the saturation of Fe-Ti oxides, consistent with observations. The modelling shows that small degrees of assimilation of sulphidic argillites of the Menihek Formation would have a significant effect on the timing of SCSS and may have played a role in sulphide segregation at Huckleberry.

6.4. Origin of sulphide mineralisation

6.4.1. Timing of sulphide melt saturation

In magmatic Ni-Cu-PGE sulphide systems, it is widely accepted that to induce sulphide saturation in a basaltic magma at low-pressure, either extensive fractional crystallisation or the addition of external sulphur is required (Ripley and Li, 2013). Results from PELE modelling indicate that the Hellancourt basalts attain SCSS after 60% crystallisation, somewhat after the onset of crystallisation of Fe-Ti oxides (Tab. 5). However, Fe-Ti oxides are confined to the upper ~ 20 m of the gabbro-peridotite sill and sulphides are concentrated at the base implying either that sulphide melt has percolated downward extremely efficiently or that SCSS was attained earlier in the crystallisation sequence.

In the Labrador Trough, Huckleberry and other similar occurrences (e.g., Hope’s Advance and Lac Retty) are characterised by Cu/Pd values above mantle range (> 10,000; Fig. 16A). This indicates that the magma equilibrated with sulphide before final emplacement, i.e., in a staging chamber or magma conduit. Previous workers (e.g., Chauval
et al., 1987; Skulski et al., 1993) hypothesised that the magmas assimilated small proportions
(< 5%) of crustal rock, based on geochemical and isotopic considerations. While
contamination remains a plausible mechanism for inducing early-onset sulphide melt
segregation, it cannot be conclusively confirmed in this study.

At Huckleberry, disseminated and net-textured sulphide horizons all possess similar
characteristics, in that: (i) Cu/Ni values range from 0.1 to 3.0, generally increasing downward
from the cumulate rocks into the glomeroporphyritic gabbro footwall, (ii) Cu/Pd values range
from 10,000 to 50,000 and display the same vertical pattern as Cu/Ni, and (iii) Pd/Ir values
range from 100 to 500. The compositional similarities combined with the downward
decreasing tails in borehole lithogeochemistry, suggest that sulphide melt has percolated from
the ultramafic cumulate units into the underlying glomeroporphyritic gabbro. This model is
similar to that proposed by Mungall (2002) at the Hope’s Advance prospect, who argued that
sulphides in the glomeroporphyritic gabbros must have percolated downward from overlying
ferropicritic units based on mass balance considerations.

6.4.2. Estimation of $R$ factors

The mass ratio of silicate to sulphide melt (or $R$ factor) exerts a critical control on the degree
of sulphide melt upgrading (Campbell and Naldrett, 1979). Komatiitic intrusions hosting the
world-class magmatic sulphide deposits elsewhere in the Circum-Superior Belt (i.e., Raglan
and Thompson Ni belts) are characterised by low $R$ factors (< 5,000; Barnes et al., 1993). To
estimate $R$ factors at Huckleberry, the closed-system equation of Campbell and Naldrett
(1979) is applied:

$$X_{\text{sul}} = X_{\text{sil}} D (R + 1)/(R + D)$$

where $X_{\text{sul}}$ is the concentration of an element in the sulphide melt, $X_{\text{sil}}$ is the concentration of
the element in the silicate magma, $D$ is the partition coefficient of the element, and $R$ is the $R$
The starting compositions are detailed in Table 4 and the partition coefficients for Ni, Cu, and PGE were 500, 1,500, and 100,000, respectively.

The disseminated and net-textured sulphides are characterised by 3-10 wt.% Ni, 10-16 wt.% Cu, and 1-6 ppm Pd. Using the starting concentration of the Hellancourt basalts, these compositions are best replicated at $R$ factors of 1,000 to 5,000. These estimations are in keeping with those determined by Cu/Pd values (Fig. 16A), whereby the Huckleberry sulphides plot at $R$ factors ranging from 500 to 10,000 at sulphide volumes of 1-10 vol.%, comparable with sulphide volumes observed in core.

6.4.3. Concentration of sulphide melt

The proportion of sulphide in the ultramafic cumulate rocks far exceeds the modelled cotectic proportion (~ 0.4 vol.%; Tab. 5). This implies that sulphide was either concentrated through hydrodynamic processes or that external sulphur was added to the magma (Maier and Groves, 2011). Geochemical evidence suggests that sulphide melt percolated downward through the basal olivine cumulates and into the glomeroporphyritic gabbro footwall. In vertical sections, chalcophile metal concentrations gradually decrease downward from ultramafic cumulates into the glomeroporphyritic gabbro footwall, whereas Cu/Pd and Cu/Ni values generally increase downward (Fig. 13; Supplementary Figure 2). Similar patterns have been ascribed to the downward percolation of fractionating sulphide melt in the Merensky Reef (Naldrett et al., 2009).

In the footwall olivine cumulates, the proportion of sulphide melt also exceeds its cotectic proportion and its composition suggests interaction with a greater volume of PGE-undepleted magma than represented in a vertical section of these relatively narrow sills. The composition of sulphide hosted in the olivine cumulate units shows several compositional
similarities (Figs. 10, 11, 12, and 16), which suggests derivation from the same initial body of sulphide melt. If the footwall ultramafic sills represent downward extensions of the gabbro-peridotite sill (discussed below), the process of downward injection could effectively funnel high proportions of sulphide melt into narrow sills via percolation and kinetic sieving.

6.4.4. Fractionation of sulphide melt

During sulphide fractionation, the Ni-rich monosulphide solid solution (mss) may become decoupled from the Cu-rich residual melt, which can be recorded in compositional changes of the sulphide melt. In Figure 16B, the composition of Huckleberry sulphides can be explained via segregation from a magma similar in composition to the Hellancourt basalts at $R$ factors ranging from 1,000 to 5,000, and a degree of fractionation from 0 to 25%. The composition of Huckleberry sulphides is comparable to that of those at Lac Bleu (Clark, 1989; 1991), which appear to have formed under similar conditions to those at Huckleberry. Disseminated sulphides from the Idefix PGE-Cu prospect occurred at higher $R$ factors (> 10,000) and likely underwent larger degrees of fractionation (Smith et al., 2019).

6.5. The architecture of the Huckleberry sill complex: Constraints on the sequence and mode of magma emplacement

The Huckleberry sill complex represents a ~ 400-m-thick stack of glomeroporphyritic and aphyric and cumulate mafic-ultramafic rocks that strike NNW-SSE and dip variably to the east (Fig. 1). A ~ 200-m-thick package of glomeroporphyritic gabbros was emplaced first (Fig. 17A). A ~ 200-m-thick differentiated gabbroic magma intruded the central part of the glomeroporphyritic gabbro sill stack and assimilated the footwall glomeroporphyritic gabbro (Fig. 17B). This unit displays normal fractionation trends with height and broadly becomes
more evolved from the south to the north of the property (Fig. 13; Supplementary Figures 1 and 2). Several ~ 30-m-thick ultramafic sills occur in the glomeroporphyritic gabbro footwall to the gabbro-peridotite sill. These sills are sulphide-rich (< 10 vol.%) and are characterised by cumulate chemistry (< 10 ppm incompatible elements).

The glomeroporphyritic gabbro sills represents a stack of plagioclase-ultraphyric basalts and share similarities to those described in the Galapagos Archipelago (Cullen et al., 1989) and Réunion Island (Valer et al., 2017), whereby plagioclase glomerocrysts comprise randomly oriented and saussurised plagioclase that display normal compositional zoning. Moreover, glomerocryst-rich intervals generally have positive Eu anomalies, whereas glomerocryst-poor intervals have negative Eu anomalies, suggesting that the glomerocrysts are composed of primocrystic plagioclase. The broader implication is that the glomerocrysts may represent autoliths that were dislodged from a floatation cumulate in a crustal staging chamber during episodic expulsion of gabbroic magma (e.g., Kushiro and Fujji, 1977; Phinney et al., 1989; Lange et al., 2013).

The differentiated gabbroic magma intruded the centre of the glomeroporphyritic gabbro sill stack, entraining immiscible sulphide melt (based on Cu/Pd > 10,000). The cumulate assemblage coarsens upward and becomes plagioclase-rich in the centre of the sill. The largest olivine crystals occur at the top of the cumulate pile, often as well sintered clusters with 120° triple junctions. Similar features have been described in the Shiant Island Main Sill (e.g., Holness et al., 2017), whereby suspended plagioclase forms the uppermost part of the cumulate pile due to its low density relative to olivine. Moreover, sintered olivine clusters atop the cumulate pile are thought to represent initially fine olivine grains that grew due to protracted suspension in a convecting sill. At Huckleberry, convection may explain the sorting observed in the cumulate pile as well as the distribution of assimilated plagioclase glomerocrysts, which can be found up to ~ 50 m above the footwall contact.
Several lines of evidence suggest that the footwall olivine cumulates represent extensions of the gabbro-peridotite sill (Fig. 17B): (i) their mineralogically and compositionally similar to the basal olivine cumulates, (ii) the footwall olivine cumulates lack an overlying liquid component, and (iii) the volume and composition of sulphides indicate interaction with more magma than that represented by a vertical section of the footwall olivine cumulates. Our model is similar to that proposed for comparable features at the Uitkomst intrusion (Maier et al., 2018), in that extensive assimilation of the footwall glomeroporphyritic gabbro resulted in the formation of troughs, from which silicate-sulphide slurries may propagate. Sulphide melt then percolated downward from the olivine cumulate layers into the footwall glomeroporphyritic gabbro.

6.6. Implication for exploration

Magmatic Cu-Ni-(PGE) sulphide occurrences in the Labrador Trough are found in the Gerido and Hurst lithotectonic zones of Clark and Wares (2005). The most prospective showings identified to date (e.g., Hope’s Advance and Lac Retty) record a protracted magmatic history comprising numerous pulses of mafic-ultramafic magma. Showings identified in the glomeroporphyritic gabbros (e.g., Lepage, Leslie, and Chrysler) are characterised by fractionated sulphide compositions (Cu/Ni > 10 and Cu/Pd > 10,000) with low grades (< 2% Cu + Ni and < 1 g/t PGE\text{Pt+Pd}). However, disseminated to net-textured sulphides identified in glomeroporphyritic gabbros may represent proximity to sulphide-rich mafic-ultramafic sills, such as that described in the present study and at Hope’s Advance (Mungall, 2002). Thick (> 100 m) differentiated gabbro sills with peridotite cumulates are the most prospective environment for magmatic sulphides in the Labrador Trough, particularly if the parental magma can effectively assimilate crustal sulphur and cool slowly enough for immiscible
sulphide to interact with a large volume of metal-undepleted magma. Sulphide-rich ultramafic protrusions may be found in the footwall to thick gabbro-peridotite sills and represent a new exploration target in the Labrador Trough.

7. Conclusions

(1) The Huckleberry Cu-Ni-(PGE) prospect in the Labrador Trough of northern Québec comprises a ~ 400-m-thick sill complex consisting of a ~ 200-m-thick glomeroporphyritic gabbro sill stack that was intruded in its centre by a ~ 200-m-thick differentiated gabbro-peridotite sill. Several ~ 30-m-thick ultramafic protrusions were injected from the gabbro-peridotite sill into the glomeroporphyritic gabbro footwall. In addition, an aphyric gabbro sill stratigraphically overlies the Huckleberry sill stack.

(2) Mineral chemistry, whole-rock geochemistry, and geochemical modelling suggest that the parent magma was olivine-saturated with 8-9 wt.% MgO. The magmatic units are characterised by relatively low La/Sm$_N$, La/Nb$_N$, and Th/Yb$_N$ values (< 2) and low S/Se ratios (< 4,000), suggesting that the magmas were not significantly contaminated by the country rocks.

(3) Disseminated to net-textured sulphides occur in the olivine cumulate units and their glomeroporphyritic gabbro footwall. Decreasing downward tails of chalcophile metals in borehole lithogeochemistry suggests sulphide has percolated downward from olivine cumulates into the glomeroporphyritic gabbro footwall.

(4) Chalcophile elements and sulphur generally show good positive correlations ($R^2$ values = Ni-IPGE > 0.74 and Pd-Pt > 0.94) suggesting that the metals are controlled by sulphide. The sulphides are magmatic in origin and are characterised by high Cu/Pd values (> 10,000) consistent with sulphide segregation prior to final emplacement. Sulphide melt equilibrated at $R$ factors of 1,000 to 5,000.
(5) At Huckleberry, disseminated sulphides in the glomeroporphyritic gabbros derive from stratigraphically overlying ultramafic cumulate horizons. Such observations have also been made at the Hope’s Advance prospect (Mungall, 2002). In some cases, mineralised glomeroporphyritic gabbros could indicate proximity to sulphide-rich ultramafic rocks in the Labrador Trough.

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**References**


https://doi.org/10.1016/j.oregeorev.2015.06.012


Clark, T., 1989. Étude du gîte de Cu-Ni-Pd-Pt du lac Bleu no 1 - Fosse du Labrador -.


Ministère de l'énergie et des ressources, Direction générale de l ….
Clark, T., Wares, R.P., 2005. Lithotectonic and metallogenic synthesis of the New Quebec
Orogen, Labrador Trough.

Corrigan, D., Pehrsson, S.J., Wodicka, N., de Kemp, E., 2009. The Palaeoproterozoic Trans-
Publ. 327, 457–479. https://doi.org/10.1144/SP327.19

activities for the Core Zone and Bounding Orogens: Recent observations from the New
Quebec Orogen in the Schefferville area, Quebec and Labrador, GEM-2 Hudson-Ungava
Project.


D’Amours, I., Intissar, R., 2003. Levé magnétique et spectrométrique aéroporté dans le
secteur du lac Romanet, Province de Churchill.


Dion, D.J., Lefebvre, D.L., 1998. Données numériques (profils) des levés geophysiques
aéroportés du Québec.

and platinum deposits [abs.], in: Geological Association of Canada-Mineralogical
Association Canada Program with Abstracts. p. 40.

Formation and Montagnais glomeroporphyritic gabbro of the central New Quebec Orogen,
Canada1 1220, 1208–1220. https://doi.org/10.1139/e95-099

Herzberg, C., Asimow, P.D., 2015. PRIMELT 3 MEGA. XLSM software for primary magma calculation: peridotite primary magma MgO contents from the liquidus to the solidus. Geochemistry, Geophys. Geosystems 16, 563–578.


https://doi.org/10.1139/e93-129


Figure Captions

Figure 1. A. The location of the Labrador Trough (or New Québec Orogen) in NE Canada and the lithotectonic divisions of the region as detailed by Clark & Wares (2005; modified from Mitchell and Smith, 2017). The Huckleberry Cu-Ni-(PGE) prospect is located in the Hurst lithotectonic zone. B. The geology of the Huckleberry prospect, including the location and attitude of boreholes drilled by Northern Shield Resources in 2016 and 2017. The white circles represent the locations of images in Figure 2. C. A schematic cross-section across the central portion of the prospect as determined by drilling and mapping (represented by the red line in part B). The stratigraphic location of sulphide-bearing horizons are annotated.

Figure 2. A. Gossanous staining on outcrops in the southern part of the property. B. Outcrop of the glomeroporphyritic gabbro in the east of the property. C. Layering in the glomeroporphyritic gabbro sill identified through sharp changes in glomerocryst size and abundance. D. Relationship between the glomeroporphyritic gabbro and ultramafic units. E. Close-up image of D showing the relationship between the glomeroporphyritic gabbro and footwall ultramafic lenses. The locations of these images are annotated in Figure 1.

Figure 3. A. Laminated metapelitic and meta-arenitic units (199 m 17HK-10). Exhalative sulphides in the Menihek Formation can occur as irregular bands (B; 347 m 16HK-01), mm- to cm-scale layers (C; 152 m 17HK-14), sulphide-bearing quartz veins/lenses (D; 77 m 16HK-05), and crackle-textured veins (E-F; 51 m 17HK-14 and 103 m 17HK-15). Drill cores are ~ 4 cm in diameter (BQ).
Figure 4. A. Drill core from borehole 17HK-12 (~ 580-660 m) showing the variability of the glomeroporphyritic gabbros. Note the glomerocryst-poor interval at the base, which is classified as the pyroxenitic glomeroporphyritic unit (PGU). B. Nature of the glomeroporphyritic gabbro with > 50 vol.% plagioclase glomerocrysts (153 m 16HK-06). C. Nature of the PGU with < 20 vol.% plagioclase glomerocrysts (228 m 16HK-06). D. Nature of the basal chilled margin of the PGU (230 m 16HK-06). E. Photomicrograph of the gabbroic groundmass of the PGU (01G). Note the degree of alteration to clinopyroxene (cpx) and plagioclase (plg). F. Photomicrograph of the glomeroporphyritic gabbro (12-630) showing the altered cores and relatively unaltered rims of plagioclase glomerocrysts. Drill cores are ~ 4 cm in diameter (BQ).

Figure 5. Ai-ii. Core intervals (117 m 16HK-07 and 493 m 17HK-12) of the basal olivine cumulates. Note the greenish, rounded plagioclase glomerocrysts assimilated from the footwall glomeroporphyritic gabbro. Aiii-iv. Photomicrographs showing fine-grained serpentinised olivine chadacrysts hosted in uralitised clinopyroxene oikocrysts (12-493 and 06O). Bi. Core interval (150 m 16HK-04) of the olivine gabbro. Bii. Olivine clusters and cumulus plagioclase hosted in a clinopyroxene oikocryst (01C). Biii. Olivine rimmed by orthopyroxene in a clinopyroxene oikocryst (12-427). Ci-ii. Core intervals (199 m 17HK-09 and 281 m 17HK-09) of the aphyric gabbro showing the variation in grain size through this unit. Ciii-iv. Serpentinised olivine grains hosted in orthopyroxene oikocrysts with cumulus plagioclase and interstitial clinopyroxene (12-392 and). Di-ii. Core intervals (79 m 17HK-08 and 198 m 16HK-05) of the titanomagnetite gabbro. Di. Thin section scan of sample 12-302 showing the distribution of Fe-Ti oxides. Div. Reflected light photomicrograph of titanomagnetite spatially associated with disseminated chalcopyrite and pyrite (12-302). Ei-ii. Core intervals (168 m 16HK-05 and 296 m 17HK-12) of the graphyric gabbro. Eiii. Cross-polarised light thin section scan of the 12-297 showing the occurrence of radial pyroxene.
Eiv. Photomicrograph showing the occurrence of quartz-feldspar granophyre, acicular actinolite-tremolite, and leucoxene (09-227). Fi-ii. Core intervals (547 m 17HK-12 and 125 m 16HK-06) of the footwall ultramafic units. Note the greenish resorbed plagioclase glomerocrysts. Fii. Partially serpentinised olivine hosted in a uralitised clinopyroxene oikocryst (06b). Fiii. Photomicrograph of a resorbed plagioclase glomerocryst (Drill cores are ~ 4 cm in diameter (BQ). ol = olivine, srp = serpentine, cpx = clinopyroxene, amph = amphibole, ilm = ilmenite, opx = orthopyroxene, plg = plagioclase, Ti-mgn = titanomagnetite, ccp = chalcopyrite, py – pyrite, lcx = leucoxene

Figure 6. Ai-ii. Core intervals (240-242 m 16HK-07) of the PGU displaying sulphide globules. Note the thick silicate caps on the globules in ii. Aiii. Architecture of a typical sulphide globule (02C) showing the lower pyrrhotite (po) margin, upper chalcopyrite (ccp) margin, and granular pentlandite (pn) at the contact. Aiv. Pentlandite exsolution lamellae in pyrrhotite (08-415). Bi. Core interval (521 m 17HK-12) showing sulphide interstitial to plagioclase glomerocrysts. Bii-iii. Photomicrographs of interstitial sulphide (09-399). Ci. Core interval (280 m 17HK-08) showing sulphide inside an assimilated plagioclase glomerocrysts. Cii. Sulphide assemblage of the basal olivine cumulates showing granular pentlandite bordered and intruded by chalcopyrite, cubanite (cbn), pyrrhotite, and ilmenite (ilm; 07-130). Ciii. Patch of net-textured sulphide hosted entirely within amphibole (07-130).

Di. Core interval (317 m 17HK-08) showing net-textured sulphides in the footwall ultramafic cumulates. Dii. Sulphide assemblage interstitial to cumulus olivine (12-554). Di.iii. Photomicrograph displayed mackinawite (mkw) exsolution lamellae and vein chalcopyrite in pentlandite bordered by cubanite and pyrrhotite (08-317). Drill cores are ~ 4 cm in diameter (BQ).

Figure 7. Binary geochemical plots underlain with olivine, orthopyroxene, clinopyroxene, and plagioclase mineral compositions. MgO against Al₂O₃ (A), FeOt (B), CaO (C), Na₂O +
Figure 8. Primitive mantle-normalised (Sun and McDonough, 1989) multi-element diagrams of the basalts and metasedimentary units (A), glomeroporphyritic gabbro units (B), titanomagnetite and granophyric gabbro (C), aphyric gabbro units (D), olivine gabbro (E), and olivine cumulate units (F).

Figure 9. A. The filtered dataset (< 0.1 wt.% S and < 200 ppm Cu) grouped into three categories: glomeroporphyritic gabbroic units, aphyric gabbroic units, and olivine-bearing units. Linear regression equations and $R^2$ values are given for each group. B. S versus pre-corrected Ni. Note that olivine cumulate samples have generally higher Ni concentrations than the glomeroporphyritic gabbros. C. S versus corrected Ni. Note how Ni concentrations of the olivine cumulates now overlap with the glomeroporphyritic gabbros. D. Ni versus calculated Ni subtract measured Ni. The majority of calculations are within 100 ppm uncertainty. See Figure 7 for legend.

Figure 10. A. Corrected Ni versus Cu. B-C. S versus Cu and PGE$_{Pt+Pd}$ + Au. Note the difference in chalcophile metal concentrations between magmatic and exhalative sulphide. D. Cu versus PGE$_{Pt+Pd}$ + Au. E. Pd versus Pt. F. S/Se versus Pt+Pd tenor. The grey field represents the mantle range from Eckstrand and Hulbert (1987). The dashed lines represent equivalent $R$ factors reported in Queffurus and Barnes (2015).

Figure 11. Ir (ppb) versus Os (A), Ru (B), Rh (C), Pt (D), Pd (E), and Au (F). For comparison, PGE concentrations of rock units from the Lac Bleu (Clark 1989; 1991) and Hope’s Advance (Mungall, 2002) occurrences have been added. Regression lines correspond
to the Huckleberry samples only. Note the good positive correlation between IPGE ($R^2 > 0.95$).

**Figure 12.** Chalcophile multi-element diagrams, normalised to Barnes and Maier (1999).

Mafic-ultramafic rocks of the Huckleberry property (coloured fields) are overlain by a Cu-rich erratic boulder at the Huckleberry prospect and disseminated sulphides from the Lac Bleu (Clark and Wares, 2005) and Raglan deposits (Barnes and Lightfoot, 2005). Chalcophile elements were recalculated to 100% sulphide using the mass balance equations of Naldrett et al. (2000).

**Figure 13** Downhole lithogeochemistry of borehole 17HK-12 at the Huckleberry prospect, displaying MgO, TiO$_2$, Cr/V, Sr, S, Ni, Cu, PGE$_{Pt+Pd} +$Au, Cu/Pd, and Pd/Pt. The colours correspond to the legend in Figure 7.

**Figure 14.** MgO versus FeO$_t$ minus FeO$_{t(sul)}$ with marginal histograms overlain with ideal compositional trends for pure olivine. Full grey lines correspond to Mg/Fe values of liquids in equilibrium with olivine based on a $K_D$ value of 0.3. The blue field represents a 95th percentile field of basaltic units (this study and Ciborowski et al., 2017). A histogram showing measured olivine compositions from this study and Rohon (1989) is provided and their colours correspond to their host rock. The composition of the parent magma is indicated where the blue regression line intersects equivalent olivine compositions consistent with those measured (see text for further discussion).

**Figure 15.** Modelling of olivine fractionation. The blue star represents the liquidus olivine in equilibrium with the Hellancourt basalt (Tab. 4) and the blue line represents olivine accumulation and removal produced in PRIMELT3 software (Herzberg and Asimow, 2015). The black line represents a result of Fe-Ni exchange between olivine and sulphide melt with 6 wt.% Ni at a $K_D$ of 12.6 (see text for discussion). Olivine compositions from Voisey’s Bay
(Li and Naldrett, 1999), Noril’sk-Talnakh (Li et al., 2003), and Jinchuan (Li et al., 2004) are overlain as 95th percentile ellipses.

**Figure 16.** A. Pd against Cu/Pd underlain with the Cu/Pd range of primitive mantle (Barnes and Maier, 1999) and overlain with $R$ factors calculations at different whole-rock sulphide volumes for Hellancourt basalt (Ciborowski et al., 2017). B. Cu/Ir against Ni/Pd underlain with mss and Cu-rich liquid tielines at different $R$ factors. Additional samples from Lac Bleu (Clark, 1989, 1991) and the Idefix PGE-Cu prospect (Smith et al., 2019) have been added.

The silicate/sulphide distribution coefficients for chalcophile metals were $D_{PGE} = 100,000$, $D_{Cu} = 1,500$, and $D_{Ni} = 500$ and the mss/sulphide melt $D$ values are of Barnes et al. (1997).

**Figure 17.** A three-dimensional cartoon illustrating the events leading to the formation of the Huckleberry Cu-Ni-(PGE) prospect. A. The glomeroporphyritic gabbros were episodically emplaced in the Menihek Formation metasedimentary rocks, whilst entraining globular sulphides at their base. B. The magma parental to the gabbro-peridotite sill was emplaced in the centre of the glomeroporphyritic gabbro sill stack, perhaps entraining sulphide (± olivine, plagioclase). During this event, assimilation of the footwall led to the propagation of olivine cumulates, which now resemble the footwall ultramafic sills. Sulphide melt percolated from the olivine- and sulphide-rich intervals into the glomeroporphyritic gabbro footwall. See text for further discussion.

**Supplementary Material**

**Supplementary Material 1.** Mineral chemistry dataset and standards.

**Supplementary Material 2.** Whole-rock and assay geochemical dataset and standards.
Supplementary Figure 1. Latitudinal geochemical changes in MgO, TiO$_2$, Na$_2$O+K$_2$O, Cr/V, Sr, Ni/Cu, Cu/Pd, and Pd/Pt in drill core intervals of the PGU, aphyric gabbro, olivine gabbro, and ultramafic cumulate units.

Supplementary Figure 2. Downhole lithogeochemistry of borehole 17HK-08 at the Huckleberry prospect, displaying MgO, TiO$_2$, Cr/V, Sr, S, Ni, Cu, PGE$_{Pt+Pd}$+Au, Cu/Pd, and Pd/Pt. The colours correspond to the legend in Figure 7.

Highlights

- New data from the recently discovered Huckleberry Cu-Ni-(PGE) prospect in NE Canada
- Unambiguous evidence for out-of-sequence formation of sill complexes
- Evidence for mobilisation of sulphide-rich crystal slurries
- Development of regional exploration criteria for orthomagmatic ore deposits
A. Globular sulphides in PGU

C. Ds to NT sulphides in basal olivine cumulates

B. Disseminated to NT sulphides in GPG

D. Ds to NT sulphides footwall ultramafic unit
Country rock: Mesobek Fe-agglomerates
Glomerophyritic gabbeo unit: Pyroxene- and plagioclase-gabbeo
Gabbro-peridotite sills: Basal ophiolites and glomerophyritic gabbeo
Other mafic units: Massee basalt, Ti-magnetite gabbeo, HW gabbeo, Footwall ophiolite, Gabbro, Ophiolite gabbeo, Mesoarc sulphide

Legend:
- Blue squares: Massee basalt
- Red triangles: Ti-magnetite gabbeo
- Green diamonds: HW gabbeo
- Black stars: Footwall ophiolite
- Yellow circles: Gabbro
- Pink stars: Ophiolite gabbeo
- Black circles: Mesoarc sulphide
- Grey triangles: Massee basalt average

Graphs A to H show the distribution of major and trace elements in the different rock units.

Ni (ppm) vs MgO (wt.%) in G.
Cu (ppm) vs MgO (wt.%) in H.