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Indicator mineral and till geochemical signatures of the Broken Hammer Cu-Ni-PGE-Au deposit, North Range, Sudbury structure, Ontario, Canada

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ABSTRACT

The Broken Hammer Cu-Ni-PGE-Au footwall deposit in the North Range of the Sudbury Structure in Canada consists of a shallow surface zone of vein- and vein stockwork-hosted mineralization within Sudbury breccia developed in the quartz monzonite Levack Gneiss Complex. The surface of the deposit consists of a 2-120 cm wide chalcopyrite vein and numerous smaller veins dominated by chalcopyrite-magnete-millerite with trace gold, platinum group minerals, tellurides, bismuthides, and selenides. The Laurentide Ice Sheet flowed southward across the region depositing a sandy till that contains abundant sperrylite (hundreds of grains), chalcopyrite, pyrite and gold in the heavy mineral fraction down ice of mineralization. Mineral Liberation Analysis of the <0.25 mm heavy mineral fraction of metal-rich till identified a broader suite of PGM and sulphides than concentration visual identification methods. The <0.063 mm fraction of till displays a strong geochemical signature of the mineralization for Pd, Pt, Au, Cu, and Ag, and to a lesser extent Bi, Te, and Sn, however, geochemical signatures are not detectable as far down-ice as indicator minerals. Till sampling has not been used for exploration in the Sudbury region because of the abundant outcrop and the use of geophysical and prospecting techniques. This study demonstrates that indicator mineral and till geochemical methods are useful exploration tools for the region. The presence of sperrylite and chalcopyrite in oxidized till indicates that even thin (<1 m) highly weathered till is an effective sample medium here.

Key words: indicator minerals, Platinum Group Minerals, sperrylite, gold grains, glacial dispersal

Few indicator mineral case studies have been conducted around magmatic Ni-Cu-PGE deposits in glaciated terrain in order to test or demonstrate indicator minerals as a viable exploration tool. To address this knowledge gap, we collected a suite of bedrock and till samples from around the magmatic-hydrothermal Broken Hammer Cu-Ni-PGE-Au deposit in the North Range of the Sudbury Structure, Ontario, Canada (Fig. 1). The specific objectives of the research project were: (1) to identify the indicator minerals indicative of the magmatic Ni-Cu-PGE mineralization; and (2) to evaluate practical methods for their recovery from glacial sediments and their identification that can be routinely applied in exploration in glaciated terrain.

The Broken Hammer deposit was used as a test site because: (1) the deposit is known to contain coarse grained platinum group minerals (PGMs); (2) bedrock and surficial geology of the area are well mapped; (3) mineralization subcrops and thus was exposed to glacial erosion; (4) the region is easily accessible by road for sampling; and (5) it is located north of the Sudbury Structure and thus up-ice of the major deposits, mines, and smelters within the region.

LOCATION

The Broken Hammer deposit is approximately 30 km north of the city of Sudbury, in Wisner Township, Ontario. It is in the North Range of the Sudbury Structure (latitude 46°45′46″N, longitude 82°57′55″W) (Fig. 1) and was accessed by a combination of
logging roads and exploration access roads and trails. The property is currently held by Wallbridge Mining Company Ltd.

GEOLOGY

Regional bedrock geology

The world-class Sudbury Ni mining district is associated with the 1.85 Ga Sudbury Igneous Complex (SIC), an elliptical body with offset dykes that straddle the boundary between the Archean Superior Province in the north and the Paleoproterozoic Southern Province to the south (Fig. 2) (Krogh et al. 1984; Corfu & Lightfoot 1997; Lightfoot & Zotov 2006). The SIC formed by brecciation and crustal melting as a result of a bolide impact. It is one of the Earth’s largest preserved impact craters.

The basement host rocks comprise Paleoproterozoic rocks of the Huronian Supergroup, dominantly metasedimentary and mafic metavolcanic rocks that have been intruded by a series of mafic magmatic dykes (Nipissing, Sudbury and Grenville dyke swarms), and minor felsic (Murray-Creighton) plutons on the southern part of the Sudbury Structure, termed the “South Range”. Basement rocks along the northern and eastern part of the Sudbury Structure, called the “North Range”, comprise Neo-Archean supracrustal and intrusive rocks deformed and metamorphosed under granulite facies conditions and form the Levack Gneiss Complex, and late Archean granite of the Cartier Batholith (Dressler 1984; Card 1994; Ames et al. 2005; Lightfoot 2016). All of these rocks were strongly affected by the shock and thermal effects of the Sudbury impact.

The shocked and brecciated basement rocks (Sudbury breccia unit) and melt rocks (Sudbury Igneous Complex) host and significantly contributed to the formation of the ores. The igneous rocks of the Sudbury Structure form the 60 x 30 km elliptical outline of the SIC along with radial and concentric, quartz diorite dykes in offset structures (Fig. 2) (Lightfoot 2016). Sudbury breccia, in the stratigraphic and structural footwall to the SIC, consists of country rock fragments in a cataclastic to pseudotachylitic matrix and forms randomly oriented stringers and large zones or “belts” of breccia found up to 200 km from the base of the SIC (Speers 1957; Lafrance et al. 2008; O’Callaghan et al. 2016a,b). Sudbury breccia represents an important mineral exploration target as it hosts Sudbury’s largest Ni-Cu-PGE deposit (Frood-Stobie), Cu-PGE, and PGE-only “footwall deposits”. Over 11.1 million metric tons of Ni and 10.8 million metric tons of Cu, along with Co, Ag, Au and PGE have been mined from this exceptional mining district (Lightfoot 2016), which remains an active region of exploration.

Sudbury Ni-Cu-PGE deposits

The Sudbury Ni-Cu-PGE deposits have been classified into three main types: contact, offset and footwall (Coats & Snajdr, 1984; Morrison et al. 1994; Molnar et al. 2001; Lightfoot 2016). Footwall-type deposits occur within 2 km of the contact zone and consist of Cu-Ni-PGE veins. They have been further divided into low-sulphide (PGE-rich) and high-sulphide (sharp-walled vein) deposits (Farrow et al. 2005; Ames & Farrow 2007). The Broken Hammer deposit has been interpreted to be a sharp-walled vein deposit. Sharp-walled Cu-Ni-PGE deposits in general are chalcopyrite-rich veins up to several metres in thickness with sharp, planar surfaces that contain
minor pyrrhotite, pentlandite, millerite, bornite, and magnetite (Farrow et al. 2005; Ames & Farrow 2007; Ames et al. 2013a).

**Local bedrock geology**
The Broken Hammer deposit is in the North Range, 1.3 km north of the SIC contact with footwall rocks of the Archean Joe Lake gabbro and/or granite and quartzofeldspathic and mafic gneiss of the Levack Gneiss Complex and Cartier batholith (Fig. 2). It was discovered in 2003 by Wallbridge Mining Company Ltd. through surface prospecting and sampling for Cu-Ni-PGE mineralization in sulphide veins. The geology of the deposit is summarized in Figure 3 and below from Peterson et al. (2004), Péntek et al. (2006, 2008), and Doran et al. (2012). Lithogeochemical data for several mineralized bedrock samples from the deposit are reported in Ames et al. (2014).

The main trench-exposed mineralization is hosted in a brecciated zone along a Matachewan-type diabase dyke in quartz monzonite. Mineralization occurs as both massive sulphide veins through the breccia dikes and as disseminated sulphides in the breccia and country rocks. One large 2 to 120 cm wide en-echelon chalcopyrite vein occurs in the centre of the trench and is informally referred to as the “Big Boy vein” (Fig. 3). Additional sulphide stringer veins are dominated by chalcopyrite-magnetite-millerite with minor pentlandite, sphalerite, bornite, covellite, bornite, and violarite (Table 1). PGM occur as inclusions in chalcopyrite and bornite or at the boundaries between various sulfides and hydrous silicates. Epidote is a common alteration mineral in the local area.

A thin (a few cm) post-glacial gossan was developed on part of the chalcopyrite vein where the vein was covered by about 3 m of till. This gossan contains abundant sperrylite, and chalcopyrite, Se-galena, cassiterite, kotulskite, merenskyite, electrum, arsenopyrite and native silver in a Fe-hydroxide matrix (Fig. 4). Trace elements in the mineral assemblages in the weathered sulfide include Pd-Pt-Sn-Pb-Au-Ag-As-Bi-Te, which are reflected in the sulfide ore lithogeochemistry (Ames et al. 2007; Péntek et al. 2008).

We sampled a stripped outcrop/trench area for bedrock and till geochemical and mineralogical studies in 2006. In 2011, a pre-feasibility study bulk sample was taken from Broken Hammer that created an open pit and removed much of the till that we sampled. New exposures in the pit revealed a “super”, high-grade sperrylite zone comprising a hydrothermal assemblage of coarse epidote-quartz-sperrylite with spectacular sperrylite crystals from <1 mm to 15 mm (Wilson 2012; Ames et al. 2013b). Based on this bulk sample and diamond drilling results, the indicated mineral resource was estimated (Sept. 12, 2013) at 259,500 tonnes at a grade of 3.80 g TPM/t (2.1 g/t Pd, 2.32 g/t Pt, and 0.77 g/t Au, 6.95 g/t Ag), 0.88% Cu, and 0.10% Ni with a reserve estimate (May 1, 2013) of 205, 000 tonnes of probable ore at 0.92 % Cu, 0.10 Ni, 2.07 g/t Pt, 1.89 g/t Pd, 0.63 g/t Au and 6.63 g/t Ag (Wallbridge Mining Company Ltd. December 12, 2013). The deposit was mined from a small open pit between 2014 and 2015 and the mine is now closed.

**Surficial geology**
The Sudbury region was most recently glaciated during the Late Wisconsinan
(25,000 to 10,000 years ago) when it was covered by the Labrador Sector of the Laurentide Ice Sheet (Boissonneau 1968; Bajc 1997a,b,c). In Wisner Township, till was deposited by ice flowing southward (175°-185°) (Bajc & Hall 2000; McClenaghan et al. 2014a). The local till on the North Range generally has a silty sand to sand matrix making it an ideal sample medium for indicator mineral and till geochemical analysis. The Wisner Township area is dominated by bedrock outcrop and thin (<2 m) discontinuous till veneer over bedrock (Bajc 1997a). Prior to the removal of the overburden in 2011, the Broken Hammer deposit was overlain by 1 to 3 m of till. In general, till across the North Range is thin (<0.5 to 3 m thick), locally-derived, loose and contains about 10 to 30% clasts. Soil has been developing on the local glacial sediments since deglaciation, about 10,000 years ago, which has produced a podzolic soil (Barnett & Bajc 2002).

Historically, till sampling has not been used to explore the Sudbury region due to the abundance of bedrock outcrop and the widespread use of surface prospecting and geophysical methods. The North Range and west side of the Sudbury Structure have more continuous till cover than the South Range, which masks the underlying bedrock. The widespread till cover in these areas provides an ideal sample medium for drift prospecting. In these areas, till can be collected from the flanks of bedrock outcrops and from till exposed in road cuts and natural sections on lakes and rivers. The North Range is also up-ice of the main Sudbury deposits, thus background metal concentrations in till will be lower than on the down-ice (south) side of the Sudbury Structure.

Previous surficial geochemical and mineralogical studies in the region
The most relevant study was that conducted by Bajc & Hall (2000) as a regional-scale till geochemical and indicator mineral survey of the North and West Range of the Sudbury Structure that included detailed studies at selected deposits/occurrences. Bajc & Hall (2000) demonstrated that till matrix geochemistry is a useful exploration method in the Sudbury region, but cautioned that the B-horizon developed on till was depleted in metals with respect to the C-horizon due to hydromorphic dispersion of metals held in sulphides. They identified Pt and Pd as well as Au, Cr, Co, Ag, Pb, As, Se, Sb, Te, Bi, Mn and Fe as pathfinder elements in till for the Sudbury Ni-Cu-PGE deposits in general, and Pd, Au, Cu and Ni as specific pathfinders around footwall mineralization. They established background contents for gold <4 grains/10 kg and zero PGM grains for till samples in their regional survey. Their highest reported gold grain abundance in till overlying mineralization was 119 grains/10 kg at the Parkin Offset dike (Fig. 2) (Bajc & Hall 2000) and their highest PGM grain count in till was 1 grain. The Broken Hammer deposit is in the central part of their study area and thus their study provides the regional context in which to interpret the Broken Hammer data.

Recently, Hashmi (2018) completed regional-scale till sampling in the southwest part of the South Range and identified sperrylite, chalcopyrite, and gold as key indicator minerals of Cu-Ni mineralization in the area. At the Vermilion offset dike deposit, she reported maximum values of 1052 sperrylite and 36 gold grains in metal-rich till and a maximal dispersal distance of less than 1500 m.
METHODS
Field sampling
A total of 38 till samples was collected in 2006 and 2015 (Figs. 2,3) around the Broken Hammer deposit for indicator mineral and matrix geochemical analyses. Sites included till sections exposed in the main trench, stripped outcrops, or clearings (Fig. 3). Samples were also collected from road cuts up to 600 m south (down-ice) (samples 06-MPB-028, 029, -031 to -034, 15-PMA-514). Samples 06-MPB-005 to -008, -030, -038 and -039 were collected 1.5 to 5 km south of the deposit and samples 06-MPB-01 to -03 were collected 6 km north of the deposit to establish background till composition. Till sample locations, site data, and site photos are reported along with till geochemical data in McClenaghan et al. (2014).

Bedrock samples were collected from the Broken Hammer deposit and surrounding host lithologies (Fig. 3) to determine the mineralogy. They were examined in polished thin section (PTS) and as a heavy mineral concentrates. Sudbury breccia samples were collected at varying distances from the main Big Boy chalcopyrite vein at Broken Hammer: 06-MPB-R02 at 0.3 m, 06-MPB-R04 at 7.5 m and 06-MPB-R13 at 109.25 m. Sample 06-MPB-R01 (small fragments) and sample 06-MPB-010 (bag of loose material) were collected from a postglacial regolith (gossan) that had developed on the mineralization (Table 2). Sample 06-MPB-R16 is an unoxidized sample of the large massive chalcopyrite vein. Samples collected from unmineralized lithologies that surround the deposit (Fig. 3) include quartz monzonite (06-MPB-R06), amphibolite (06-MPB-R07 proximal to mineralization, 06-MPB-R12 distal to mineralization), gabbro (06-MPB-R08), and diabase (06-MPB-R11). Bedrock sample locations, site data, and photographs are reported in McClenaghan et al. (2018a).

Sample processing and indicator mineral recovery
Processing methods used to recover indicator minerals from bedrock and till samples are described in detail in McClenaghan & Ames (2013). The mass of all fractions and splits produced for each till and bedrock sample, along with the number of indicator minerals counted and flow charts, were reported by McClenaghan & Ames (2013) and McClenaghan et al. (2018a,b). Large till samples (~15 kg) and gossan sample 06-MPB-010 were processed at Overburden Drilling Management Ltd. (ODM), Ottawa, to produce non-ferromagnetic heavy mineral concentrates for examination of indicator minerals. Briefly, the <2.0 mm fraction of samples was passed over a shaking table to produce a preconcentrate. The preconcentrate was micro-panned to recover gold, sulphide, and PGMs. Gold and sperrylite grain counts reported in Table 2 are the result of this processing step. The gold grains were classified using the graphically descriptive scheme (pristine-modified-reshaped) of DiLabio (1990) to relate grain shape, crystal face, and surface textures to glacial transport distance. All panned grains were then returned to the preconcentrate. The <2.0 mm preconcentrate was then further refined using heavy liquid separation in methylene iodide diluted to a specific gravity (SG) of 3.2. The ferromagnetic fraction was then removed from the concentrate and the non-ferromagnetic heavy mineral fraction was sieved into three size fractions: 0.25–0.5, 0.5–1.0, and 1.0–2.0 mm and examined for indicator minerals. Bedrock samples were crushed to <2.0 mm, micro-panned, and then refined using the same heavy liquid and ferromagnetic separation procedures used for the till samples.
To test the usefulness of examining the mineralogy of the <0.25 mm heavy mineral fraction, Mineral Liberation Analysis (MLA) was applied to metal-rich (Au, Cu, Pt, Pd, Ag, Bi, Te, Ni) till sample 06-MPB-012. The sample, weighing 43 g, was dry sieved into five smaller size fractions (180-250 µm, 125-180 µm, 75-125 µm, 45-75 µm, and <45 µm) that were then processed using hydroseparation by CNT Mineral Consulting Inc., Ottawa (Rudashevsky et al. 2002; Cabri et al. 2008; McDonald et al. 2017). Hydroseparation is an efficient means of separating very small amounts of dense minerals and observing rare mineral species that may not be detected or present in coarser heavy mineral fractions. The hydroseparation concentrates were mounted in 3 mm diameter circular epoxy mounts and examined using the MLA facilities at Activation Laboratories, Ancaster, to identify the minerals present. All polished sections were analyzed using a MLA-600F SEM at an accelerating voltage of 25 kV and spot size of 6 µm. The MLA was equipped with two Bruker 5010 EDS X-Ray Spectrometers and a standard, four-quadrant back-scattered electron (BSE) detector. Mineral abundances were reported in volume % and weight % as determined by MLA. Although the MLA data were reported to 2 decimal places, the detection limit is 0.1 %. Consequently, data reported as less than 0.1 % should be treated as semi-quantitative only. SEM EDS analysis of selected gold and PGM grains was then completed using the same system.

Geochemical analysis
The <0.063 mm fraction of till samples was analyzed by ACME Laboratories (now Bureau Veritas Minerals), Vancouver using lithium meta/tetraborate fusion and nitric acid digestion on a 0.2 g aliquot followed by ICP-ES and -MS detection. A separate 0.5 g split was digested in modified aqua regia (1-1 HCl-HNO₃) and analyzed by ICP-MS. The elements Au, Pt, and Pd were also determined by Pb-collection fire assay/ICP-MS on a 30 g aliquot. Analytical accuracy and precision were monitored using CANMET certified reference standards and lab preparation and analytical duplicates. All results are reported in McClenaghan et al. (2014). Based on evaluations of the reported QA/QC data, the analytical data were deemed acceptable for further interpretation.

RESULTS
Visual indicator minerals
Visual indicator mineral counts for the <2.0 mm panned fractions and the 0.25-0.5 mm heavy mineral concentrates of till samples were normalized to a 10 kg sample mass (<2 mm table feed) to allow comparison between samples of varying mass. Indicator mineral counts for bedrock samples were normalized to a 1 kg sample mass (<1 mm fraction). Normalized values for both till and bedrock samples are listed in Table 2 and discussed below. Normalized values for selected minerals in till samples are plotted as proportional dot maps and colour photographs of selected indicator minerals are included in Figure 5.

Platinum Group Minerals
Bedrock: Sperrylite (PtAs₂) is a platinum group mineral (PGM) that is easily recognizable in pan concentrates by its bright silver white colour (Fig. 5a-b). It is hard (H=6 -7) and dense (10.58 g/cm³). Gossan sample 06-MPB-010 contained 59 grains of sperrylite in the pan concentrate (Table 2) as well as nine coarser grains in the 0.25 – 0.5 mm heavy mineral concentrate. Sperrylite grains recovered from the 0.5 –
1.0 mm and 1.0 – 2.0 mm fractions of the sample are aggregates of sperrylite (silver) + goethite (orange) + chalcopyrite (yellow) (Fig. 5a). Gossan sample 06-MPB-R01 contained 54 grains of sperrylite in the pan concentrate (Table 2). A sample of unoxidized massive chalcopyrite (06-MPB-R16) contained an estimated 150 grains of PGM in the pan concentrate. SEM checks on three of the grains indicated that two were michenerite [(Pd,Pt)BiTe] (25–50 µm) and the other was tellurobismuthite (Bi$_2$Te$_3$), 150 µm in size.

Till: No sperrylite grains were recovered from background till samples 06-MPB-001, -002, and -003 up-ice of the deposit or in the regional till samples collected by Bajc & Hall (2000). Till samples proximal to (within 10 m), and overlying mineralization contain between zero and 714 sperrylite grains/10 kg in the pan concentrate (Table 2; Fig. 6). Between 10 and 50 m down-ice, till contains tens of sperrylite grains; between 50 and 300 m down-ice till contains a few grains up to a maximum of 21 grains. Sample 06-MPB-031, collected 600 m down-ice, contains 21 sperrylite grains. Four grains were recovered from sample 06-MPB-08, 10 km down-ice of mineralization (Fig. 6).

Sperrylite grains recovered from till sample 06-MPB-026, 50 m down-ice (south) of mineralization include angular anhedral fragments of broken grains up to 100 µm (Fig. 7A to F) and smaller (20 µm) euhedral crystals (Fig. 7G-H). Sperrylite grains recovered from till sample 06-MPB-033, 170 m down-ice of the mineralization, include a euhedral crystal and an angular anhedral fragment (Fig. 8A-B), both 50 µm in diameter. All sperrylite grains recovered and reported in Table 2 were in the pan concentrate and were between 25 to 100 µm in diameter, with majority of grains being between 25 and 50 µm in diameter (Table 3). In addition to these small grains, 1 to 3 individual sperrylite grains were recovered from the 0.25-2.0 mm heavy mineral fraction of till samples 07-MPB-011, -012, and -027, located between zero and 10 m down-ice.

**Gold**

Bedrock: Gold was easily identified in the pan concentrate by its bright yellow colour and high density (16-19.3 g/cm$^3$). A total of 33 gold grains were visually identified in the pan concentrate of bedrock gossan sample 06-MPB-R01 and 42 gold grains/kg in amphibolite sample 06-MPB-R07 (Table 2). Gold grains in bedrock varied in size from 15 to 150 µm, but most were 50 µm or less. Gossan sample 06-MPB-010 contained 176 gold grains (Table 2). All gold grains recovered from bedrock samples were classified as pristine in shape, according to the gold grain shape classification scheme of DiLabio (1990).

Till: Metal-rich till proximal (within 10 m) and overlying mineralization contained between 2 and 456 gold grains/10 kg (Table 2). Between 10 and 50 m down-ice, till contained tens of gold grains; between 50 and 300 m down-ice, till contained ones to tens of grains. Samples 15-PMA-514 and 06-MPB-031, between 500 and 600 m down-ice, contained 6 and 9 gold grains, respectively.

Gold grains recovered from till varied in shape from pristine to modified to reshaped (DiLabio, 1990) with most of the gold grains recovered being pristine. Till samples 06-MPB-11, -12, -18, -25, -26 and -27 closest to the deposit contained the greatest
number of pristine grains, most of which are 75 µm or less (Table 3). Pristine grains reflect a short glacial transport distance and proximity (<1 m) to mineralization.

**Chalcopyrite**

Bedrock: Chalcopyrite was identified in the heavy mineral by its bright yellow metallic appearance (Fig. 5c). It is moderately dense (4.1-4.3 g/cm$^3$) and relatively soft (H=3.5) as compared to sperrylite. Hundreds of thousands of chalcopyrite grains/kg were recovered from the 0.25 – 0.5 mm heavy mineral concentrate of massive chalcopyrite sample 06-MPB-R16 and gossan sample 06-MPB-R01. Gossan sample 06-MPB-010 contained tens of thousands of grains. Host and background bedrock lithologies at Broken Hammer contained between zero to 5 grains/kg, which was considered to be background content in all local lithologies.

Till: Chalcopyrite was by far the most abundant ore mineral in till down-ice of mineralization (Fig. 10). Bajc & Hall (2000) did not report the abundance of chalcopyrite in their regional till samples, therefore we used the chalcopyrite content of pyrite in till samples 06-MPB-001, -002, and -003 (Table 2) up-ice of the deposit to establish the threshold between background and anomalous contents. Till overlying mineralization at Broken Hammer contained up to 16,000 chalcopyrite grains. Between 10 and 50 m down-ice, till contained one to ten grains; between 50 and 300 m down-ice, till contained zero to 5 grains. Sample 06-MPB-031, collected 600 m down-ice, did not contain chalcopyrite. Most till samples between zero and 170 m down-ice of mineralization also contained at least a few grains of coarser 0.5-2.0 mm chalcopyrite grains.

**Pyrite**

Bedrock: Pyrite was identified in the heavy mineral by its pale yellow metallic to highly oxidized brown colour and its cubic crystal habit (Fig. 5c). It has a density of 5 g/cm$^3$ and is harder than chalcopyrite (H=6.5). Bedrock samples 06-MPB-R12, -R13, and -R17 contained the most pyrite; 100s to 1000s of grains/kg (Table 2). No pyrite was recovered from gossan samples 06-MPB-R01 and 06-MPB-010 or from massive chalcopyrite samples 06-MPB-R16.

Till: Bajc & Hall (2000) did not report the abundance of pyrite in their regional till samples, therefore we used the content of pyrite in till samples 06-MPB-001, -002, and -003 to establish the threshold (Table 2). At Broken Hammer, till overlying mineralization contained tens of grains up to a maximum of 104. Between 10 and 50 m down-ice, till contained up to 127 grains (Table 2), between 50 and 300 m down-ice, till contained up to 132 grains.

**Other Minerals**

Other minor sulphide minerals visually observed in polished thin sections or bedrock heavy mineral concentrates (Table 2) include pyrrhotite, bornite, millerite, chalcocite, covellite, galena, and sphalerite. Secondary minerals observed include malachite, hematite, goethite, and jarosite. Pyrrhotite, bornite, galena, hematite, and goethite were also present in the till.
MLA analysis of heavy mineral concentrates
MLA was performed on the <0.25 mm heavy mineral concentrate of gossan sample 06-MPB-R01 and the relative abundance of the Pt-Pd-As-Sn minerals in this fraction are summarized in Figure 4 from Ames et al. (2007). PGMs comprise one half of minerals detected. Sperrylite is by far the most abundant and comprises a little more than 1/4 of the sample and kotulskite + merenskyite + michenerite comprise another 1/4 of the sample. Cassiterite and galena are second and third most abundant (Fig. 4) and together make up almost one half of the minerals. Silver, electrum, and arsenopyrite make up a very small percentage of the minerals.

MLA was used to examine the mineralogical composition of the <0.25 mm fraction (split into 5 size fractions) of till sample 06-MPB-012, overlying mineralization. Table 4 lists the mineralogy of the 5 fractions and Table 5 lists the specific precious metal minerals that were confirmed to be present. Most chalcopyrite and pyrite are in the coarser size fractions (180-250 and 125-180 µm). Very minor amounts of galena, pyrrhotite, bornite, and pentlandite were detected in the <45 µm fraction. Also in the finer size fractions, altered species are more common, including “Pd-Oxide” (0.19 %) and Fe- and Fe-Cu-sulphates, in which disseminated <45 µm bornite occurs. The “Pd-oxide” was not further studied but is likely a mixture in an altered Pd-telluride or Pd-bismuthtelluride mineral. Cassiterite, gold, and sperrylite are most abundant in the three finer fractions (75-125 µm, 45-75 µm, and <45 µm fractions).

A small percentage (<0.17% vol) of the minerals in each size fraction are listed as ‘other’ in Table 4. Collected spectra that do not meet the user-designated matching parameters (as a percentage) for any reference in the project mineral reference library will be included in ‘other’. These minerals may be unidentified because they are not present in the mineral reference library, a mixture of multiple minerals present in the excitation volume of the electron beam produced complicated overlapping spectra, or damaged/fractured grains that did not provide a planar surface for beam interaction. For more information on possible sources of error in MLA see Sandmann (2015).

Till geochemistry
Bajc & Hall (2000) reported regional geochemical data and percentile values for the <0.063 mm fraction of for the Sudbury North Range. These published values were used to provide a regional context to interpret the Broken Hammer data and the values for the two studies are compared below. Their 95th percentile values for Au, Pt, Pd, Cu, Ni and Ag are reported in Table 2.

Platinum, Palladium, and Gold
Platinum concentrations in till determined by Fire Assay/ICP-MS at the Broken Hammer range from 0.7 to 245 ppb. Palladium values in till are generally higher than Pt and range from 0.7 to 509 ppb (Table 2). Platinum values were highest in till samples collected between 0 and 10 m south (down-ice) (sample 06-MPB-011, -012) of the main chalcopyrite vein. Sample 06-MPB-13, collected 25 m west of the main chalcopyrite vein also had elevated values of Pt (26 ppb) and Pd (59 ppb).

Till samples proximal (within 10 m) to mineralization contained between 2 to 97 ppb Au (Fig. 11), with till samples 06-MPB-011 and -012 containing the most Au (70 to 90
ppb). All other till samples contained background concentrations of Au as compared to the regional threshold of 30 ppb (Table 2).

**Copper and Nickel**
Copper content in till samples for this study were highest overlying and within 10 m of mineralization, with maximum values of 1182 to 3454 ppm in samples 06-MPB-011 and -012, respectively (Table 2). Between 10 and 50 m from mineralization, Cu values range from 63 to 757 ppm. Beyond 50 m distance, samples contain 32 to 95 ppm Cu.

Similar to Cu, the highest Ni values in till are in samples 06-MPB-011 and -012 (Table 2) which contain 344 ppm and 101 ppm Ni, respectively. Between 10 and 50 m from mineralization, Ni values range from 21 to 133 ppm. Beyond 50 m from mineralization, samples contain very low concentrations of Ni between 16 to 66 ppm.

**Other elements**
The highest concentrations of Ag (159 ppb) (Table 2), Cd (0.29 ppm), Sb (0.21 ppm), Bi (3.57), Te (2.09 ppm), and Se (1.0 ppm) were in till samples 06-MPB-011 and -012, overlying mineralization. Elevated Ag values were also found in till samples 06-MPB-022 (115 ppb) and 06-MPB-023 (98 ppb), located <4 m from the main sulphide vein. Two Sn values stand out as being high as compared to the other till samples (1-4 ppm); 06-MPB-012 contained 7 ppm and 06-MPB-014 contains 14 ppm Sn.

**DISCUSSION**

**Mineralogy**
The main indicator minerals visually identified in mineralized bedrock samples include chalcopyrite, PGM (sperrylite, michenerite), and gold. The postglacial gossan developed on the massive chalcopyrite vein contained the same minerals as well as chalcocite and secondary minerals goethite, malachite, and jarosite, - typical secondary minerals associated with oxidized Cu-sulphide deposits (e.g. Bower et al. 1995; Boyle 2003). Minerals identified using MLA of the <0.25 mm bedrock fraction are the same but also include kotulskite, merenskyite, cassiterite, silver, and arsenopyrite.

The main indicator minerals visually observed in till samples included chalcopyrite, pyrite, sperrylite, and gold. Between 0 and 50 m down-ice, till contained tens to hundreds sperrylite grains, tens to hundreds of gold grains, and tens to thousands of chalcopyrite grains. Between 50 m and 300 m down-ice, till contained only a few (0-2) sperrylite grains, several (2 to 16) gold grains, and ones of chalcopyrite grains. Beyond 300 m down-ice, the spacing of the till samples was not sufficient to determine the maximum distance down-ice that indicator minerals from the Broken Hammer may be detected. However, one till sample collected 600 m down-ice did contain sperrylite. These grains are likely derived from the Broken Hammer deposit because of their proximity. It is possible they were eroded from an unknown mineralized zone between the deposit and the sample site.

Ore minerals detected in till using MLA are the same, but also included pentlandite, pyrrhotite, galena, bornite, michenerite, moncheite, merenskyite, Fe-Cu sulphates, and Fe oxides.
Indicator mineral size
Most gold grains in the gossan heavy mineral fraction were 10 to 75 µm. Gold grains recovered from the pan concentrates of till samples were mainly 25 to 75 µm in diameter (Table 3). This observation of the general size range of gold was confirmed by MLA analysis of the <0.25 mm fraction of till sample 06-MPB-012 (Table 5). A few coarse (up to 250 µm) gold grains were recovered from till.

Sperrylite grains recovered from the gossan sample were 100 µm in diameter. MLA analysis of the <0.25 mm heavy mineral fraction of till sample 06-MPB-012 indicated that sperrylite was present in all five subfractions, but most abundant in 75-125 µm and 45-75 µm fractions (Table 5). Most sperrylite grains recovered from till pan concentrates were 25 to 50 µm in diameter (Table 3). A few coarse grains of sperrylite (up to 1.0 mm diameter) were recovered from the >0.25 mm heavy mineral fraction of proximal (<10 m down-ice) till samples. These large grains in till are not unexpected because large sperrylite crystals up to 15 mm occur in the deposit.

Most chalcopyrite grains recovered from till were 0.25-0.5 mm in diameter. Within 170 m down-ice, till samples also contain a few grains of coarser (0.5 to 2.0 mm) chalcopyrite grains. Till sample 06-MPB-006, at the Wisner West deposit also contains two coarse chalcopyrite grains. The presence of coarse chalcopyrite in till is an indicator of close proximity to massive sulphide mineralization.

Indicator mineral shape
Approximately 86% of the gold grains were recovered from bedrock sample 06-MPB-010 indicating that the Broken Hammer mineralization is the source of the pristine grains in the local till. About 60% of the gold grains recovered from till samples were pristine in shape, with till samples overlying and up to 40 m down ice of mineralization (samples 06-MPB-11, -12, -18, -25, -26 and -27) containing most of the pristine grains. This distribution indicates that at Broken Hammer, pristine gold grain shape is a strong indicator of proximity to mineralization.

PGM morphology that has been reported to date is from studies of placer and alluvial occurrences (McClenaghan & Cabri 2011). This paper is one of the first to describe and show images of the shape of sperrylite grains recovered from glacial sediments. Euhedral sperrylite crystals, similar in shape to those reported by Wilson (2012) for Broken Hammer ore, were recovered from till up to 170 m down-ice. The presence of these euhedral grains indicates that glacial comminution had little impact on some of these hard (H = 6-7) mineral grains, or that grains were liberated from larger ore fragments in till during postglacial weathering or, some combination of both.

Till geochemistry
Source of high metal contents in till
Platinum, palladium and gold
The high Pt (max 245 ppb) and Pd (max 509 ppb) values in till at the Broken Hammer site are some of the highest reported in the literature for the <0.063 mm fraction of till, and significantly higher than the 95th percentile values for the North Range region reported by Bajc & Hall (2000). The high concentrations in proximal till are not unexpected as abundant sperrylite grains were recovered from the heavy
mineral fraction of the same till samples (Table 2). The high Pt and Pd values in till likely reflect not only the presence of sperrylite but also the other PGM listed in Table 1 that have been reported in the mineralized zone (Watkinson et al., 2005; Péntek et al. 2008; Ames and Kjarsgaard, 2013). This is confirmed by the presence of sperrylite, michenerite, moncheite, and merenskyite in the <0.25 mm fraction identified by MLA (Table 5). Elevated Pt and Pd values, as well as Cu, Ni, and Bi, in till sample 06-MPB-13, 25 m west the Big Boy vein may indicate the presence of a western extension of this vein system or a source slightly to the north (up ice).

Gold values in the <0.63 mm fraction of till around the Broken Hammer occurrence were significantly greater than the 95\textsuperscript{th} percentile (29.5 ppb) reported by Bajc & Hall (2000). Elevated Au concentrations (15 to 97 ppb) in till samples were confirmed by the presence of abundant fine grained gold grains recovered from the pan concentrates (Table 2) and detected in the <0.25 mm fraction of sample 06-MPB-012 using MLA (Table 4). Gold's strong correlation with Pt and Pd was expected because the same samples that contain abundant gold grains also contain abundant sperrylite. The close association of Au with Pt and Pd in the till is supported by the observations of PGM and gold in the gossan sample. Péntek et al. (2008), however, reported very weak correlations (r<0.30) between Au and Pt and Pd for the Broken Hammer deposit.

\textit{Copper and Nickel}

Till down-ice of the main vein contained 100s to 1000s ppm Cu that are significantly greater concentrations than the 95\textsuperscript{th} percentile reported for the North Range region (Bajc & Hall, 2000). These elevated Cu values in till were usually accompanied by 10s to 1000s of chalcopyrite grains/10 kg (Table 2). MLA analysis of sample 06-MPB-12 confirmed the presence of chalcopyrite and bornite in the <0.25 mm heavy mineral fraction (Table 4). Other minor Cu-bearing minerals present in the Broken Hammer deposit (Table 1) that likely contributed to the Cu signature in till at Broken Hammer include covellite, wittichenite, emplectite and malyshevite (Table 1).

Four till samples contained elevated Ni concentrations (101 to 344 ppm) greater than the 95\textsuperscript{th} percentile (97 ppm) reported for the North Range region (Bajc & Hall 2000). These four samples are metal-rich and close to the main vein. MLA analysis of sample 06-MPB-12 suggests that the presence of pentlandite in the <0.25 mm heavy mineral fraction (Table 4) could be the source of the Ni. The weaker Ni signature in the till, as compared to Cu, reflects the relatively low abundance of Ni-bearing minerals in the Broken Hammer sulphide veins (Ames et al. 2007; Péntek et al. 2008), and in general in other North Range footwall deposits (Farrow et al. 2005). The low Ni concentrations in till could also reflect the instability of Ni-bearing minerals in the surface weathering environment.

\textit{Other elements}

Till samples 06-MPB-011 and -012 overlying the main vein contain elevated concentrations of Bi (3.6 ppm) and Te (2.1 ppm) as compared to the other Broken Hammer till samples and regional till samples collected by Bajc & Hall (2000). MLA analysis of sample 06-MPB-12 suggests that the presence of michenerite, moncheite, and merenskyite in the <0.25 mm heavy mineral fraction (Table 5) could be the source of the Bi and Te.
Elevated Ag concentrations (159 ppb) in till samples 06-MPB-011, -012, -022 and -023, overlying or just down-ice of the main vein, likely reflect the presence of the silver-bearing minerals such as hessite, electrum, naumannite, volynskite, and native silver in the main vein or gossan (Table 1). No silver bearing minerals were detected using MLA.

The two highest Sn values in till samples may reflect the presence of cassiterite in the deposit (Table 1). MLA analysis identified a significant amount of cassiterite as being present in the <0.25 mm heavy mineral fraction of sample 06-MPB-012.

Considering the large number of sperrylite (PtAs$_2$) grains (up to 700 grains/10 kg) recovered from till samples proximal to the main vein, it is surprising that As concentrations in till are low (<3.0 ppm) in both weathered and unweathered till. In contrast, arsenopyrite-bearing till at the Sisson W-Mo deposit contains up to 745 ppm As (McClenaghan et al. 2014b). The low concentrations of As in the <0.063 mm fraction of till at Broken Hammer indicates that elevated Pt contents in the till are derived from non-As bearing PGM as well as from sperrylite.

**Indicator and pathfinder elements**

Indicator elements are ore-forming elements for which elevated concentrations may be indicative of the presence of mineralization (Rose et al. 1979). Our results indicate that Pd, Pt, Cu, Ni, Au, and Ag are indicator elements in the <0.063 mm fraction of till for the Broken Hammer deposit. Pathfinder elements are non-ore elements for which elevated concentrations may be indicative of the presence of mineralization (Rose et al. 1979) and at Broken Hammer include Bi, Te and Sn. Our list of elements is similar to that of Péntek et al. (2008) who identified In, Te, Sn, Bi, As, Cd, Co, and Zn as the best indicator elements in bedrock, for footwall-type Cu-Ni-PGE deposits in the Wisner area.

**Advantages of till geochemistry**

Till geochemistry is an inexpensive and routine exploration method that has been used in Canada for more than 50 years (McClenaghan & Paulen 2017). It is now a widely used tool for Ni-Cu-PGE exploration (e.g. Tardiff 2000a,b; Bajc & Hall, 2000; Hashmi, 2018; McClenaghan et al. 2011; Brownscombe et al. 2015; Santaguida et al. 2015). The <0.063 mm till fraction at Broken Hammer clearly shows the geochemical signature of the deposit. However, in this study it was not able to detect metal-rich debris more than 125 m down-ice of the deposit. Such a short dispersal distance means that sample spacing would need to be <2 km to be effective in detecting such a short train.

**Advantages of indicator mineral methods**

This study has demonstrated the benefits of using indicator mineral methods to detect Cu-PGE mineralization. Sperrylite was used to detect glacial dispersal at least 600 m down ice of mineralization, farther than that defined by till geochemistry. The indicator minerals (sperrylite, gold, chalcopyrite) are physical evidence of the presence of mineralization and can be examined and photographed with a binocular and/or scanning electron microscope and their morphology described. Just a few grains in a 10 kg till sample can be an indication of the presence of mineralization...
even when the geochemical composition of the till (Pt, Pd, Cu, Au) was below threshold (e.g., sample 06-MPB-031; Table 2). An additional advantage is that the grains may be chemically analyzed in the future to provide information about the nature of the mineralizing system (e.g., trace elements and inclusions in gold and chalcopyrite).

Indicator mineral counting using the >0.25 mm heavy mineral fraction is a well established method (e.g. McClenaghan 2005; 2011) and has been used for more than 30 years by the Canadian industry and government and thus, results reported here can be directly compared to those for the Sudbury region conducted by Bajc & Hall (2000) and Hashmi (2018). The method is routine, fast, and moderately priced and the identification of Cu-Au-PGE minerals can be conducted as part of indicator mineral surveys conducted for other commodities (i.e., diamonds, precious or base metals).

Use of automated mineralogy methods (MLA) to examine the <0.25 mm fraction of a till sample in this study required the <0.25 mm heavy mineral to be sieved into smaller fractions, the heavy minerals further concentrated, and heavy grains to be mounted prior to mineral identification. The additional time and cost of MLA was deemed worthwhile to confirm the presence of ore and indicator minerals that were suspected to be present based on general knowledge of the mineralogy of the deposit combined with the high metal concentrations in the till matrix. MLA identified additional indicator minerals that were not visually identified in the >0.25 mm heavy mineral fraction using traditional methods (cassiterite, bornite, pentlandite, pyrrhotite, galena, michenerite, moncheite, and merenskyite). These minerals likely were not visually identified in the pan concentrates or >0.25 mm heavy mineral fraction because they are smaller than 0.25 mm or occur as inclusions in other larger mineral grains.

MLA software was first developed for use in the metallurgical industry to determine mineral size, shape and intergrowths of mineral processing products (Burrows & Gu 2006; Gu et al. 2012; Layton-Matthews et al. 2017). The application of MLA to till mineralogy has been tested by a few researchers (e.g. Wilton & Winter 2012; Lehtonen et al. 2015) but is still relatively new. The results presented here are the first to be reported along with, and compared to, conventional (>0.25 mm) till indicator mineral methods.

In Canada, indicator mineral methods can now be used in exploration programs and government surveys to evaluate the potential of a region to host a broad range of commodities including gold (Averill 2001, 2013; McClenaghan & Cabri 2011), diamonds (Averill 2001; McClenaghan & Kjarsgaard 2007 and references therein), porphyry Cu (Averill 2011; Plouffe et al. 2016; Plouffe & Ferbey 2017), volcanogenic massive sulphide (Averill 2001; McClenaghan et al. 2015a,b), Mississippi Valley-Type Pb-Zn (Oviatt et al. 2015; McClenaghan et al. 2018c), and granite-hosted Sn and W (McClenaghan et al. 2016, 2017). This case study, combined with those conducted around other Ni-Cu-PGE deposits (Averill 2011; McClenaghan et al. 2013; Hashmi 2018) demonstrate that Ni-Cu-PGE indicator minerals should be included in this list of deposit types.
CONCLUSIONS

This study was carried out to demonstrate that indicator minerals are a viable exploration tool for Cu-Ni-PGE deposits in the Sudbury mining district. The indicator minerals indicative of the Broken Hammer Cu-Ni-PGE deposit include chalcopyrite, pyrite, sperrylite, and gold. These minerals are visually distinct and easily recovered by common heavy mineral processing methods from the >0.25 mm fraction. Sperrylite is the most abundant indicator mineral in the till and grains as large as 2 mm were recovered from the till. It is an ideal indicator mineral for the Sudbury mining district because is reasonably physically robust, resists chemical weathering in the surface environment (oxidized till), and is visually distinct. Earlier till studies around deposits on the Sudbury North Range and elsewhere in Canada provided little insight to PGM content as they only reported the recovery of rare PGM grains in a few till samples.

As a follow up to conventional indicator mineral methods and till geochemistry, MLA was used to identify precious metal and sulphide minerals in the fine (<0.25 mm) heavy mineral fraction of till. The mineral hosts of Pt, Pb, Bi, Te, Cu, Ni, and Sn were identified which helped to explain patterns in the <0.063 mm till geochemistry. Because only one till sample was examined the background contents of these minerals in till up-ice of the mineralization is not known. MLA of additional till samples around Broken Hammer will establish background values and protocols to routinely apply to Cu-Ni-PGE indicator mineral surveys. This method has the potential to decrease indicator mineral characterization time and cost as it becomes more widely tested and applied. In addition to MLA, mineral chemistry characterization of both the bedrock and till using tools such as laser ablation/ICP-MS would also provide additional insights into the deposit signature and glacial dispersal.

The indicator elements in the matrix (<0.063 mm) fraction of till down-ice of this Cu-(Ni-)PGE footwall deposit include Pt, Pd, Cu, Ni, Au and Ag. Pathfinder elements include Bi, Te, and Sn. Till geochemistry is also a useful tool for exploration in the Sudbury region, however geochemical signatures are not detectable as far down ice as indicator minerals.

Implications for Exploration

Historically, till sampling has not been used for Cu-Ni-PGE exploration in the Sudbury region. It will be most effective in the north and west parts of the Sudbury Structure, i.e., up-ice (north) of the main Sudbury deposits, where till cover is thicker and more continuous, bedrock outcrop is less abundant, and possible anthropogenic contamination of soils related to mining and smelting is minimal.

Till can most easily be collected from the flanks of bedrock outcrops, and from till exposures in road cuts and along lake and river shorelines in the Sudbury region. Because of the small size (tens of metres) of footwall deposits, an effective till sample spacing would be <2 km for a regional-scale survey, and <50 m for a property-scale survey.

Till in the region is thin (<2 m), thus weathered till may be the only sampling medium available at some sites. Though unoxidized till is the optimal sample medium, the
presence of sperrylite and some chalcopyrite in the oxidized till indicates that thin, oxidized till is also worthwhile sampling if it is the only medium available.

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| Precambrian | Middle and Early Proterozoic |
|-------------|-----------------------------|
| Grenville Province gneiss and intrusions |
| Felsic plutonic rocks |
| Early Proterozoic | Sudbury Igneous Complex |
| Norite, sublayer |
| Granophyre |
| Whitewater Group | Chelmsford Formation |
| Onwatin Formation |
| Onaping Formation |
| Huronian Supergroup |
| Cobalt Group |
| Quirke Lake Group |
| Hough Lake Group |
| Elliot Lake Group |
| Archean |
| Felsic plutonic rocks |
| Levack Gneiss Complex |
| Beatty, Moose Mtn greenstone belts |
| Ni-Cu-PGE, Cu-PGE, Ni-Cu mines |
| Mineral                  | Formula       | Hardness | Density       | At Broken Hammer, Identified by others | Identified in PTS this study | Identified in bedrock HMC this study | Identified in till HMC this study | 0.25-0.5 mm |
|-------------------------|---------------|----------|---------------|----------------------------------------|------------------------------|-------------------------------------|----------------------------------|-------------|
| **Sulphides**           |               |          |               |                                        |                              |                                     |                                  |             |
| arsenopyrite             | FeAsS         | 5        | 6.07          | Ames et al. (2007)                      | no                           | no                                  | no                               |             |
| bornite                 | Cu₃FeS₄       | 3        | 4.9 - 5.3     | Péntek et al. (2008)                    | yes                          | no                                  | no                               |             |
| chalcopyrite            | CuFeS₂        | 3.5      | 4.1 - 4.3     | Péntek et al. (2008)                    | yes                          | yes                                 | yes                              |             |
| covellite               | CuS           | 1.5-2    | 4.6 - 4.76    | Péntek et al. (2008)                    | yes                          | no                                  | no                               |             |
| clayerite               | PtBi₂S₄⁺        | 3        | not reported  | Péntek et al. (2008)                    | no                           | no                                  | no                               |             |
| galena                  | Pb(S,Se) +Bi₄Ag | 2.5      | 7.2 - 7.6     | Ames et al. (2007)                      | no                           | yes                                 | no                               |             |
| millerite               | NiS            | 3-3.5    | 5.5           | Péntek et al. (2008)                    | yes                          | no                                  | no                               |             |
| pentlandite             | (Fe,Ni,Co)₂S₂   | 3.5-4    | 4.6 - 5       | Péntek et al. (2008)                    | no                           | no                                  | no                               |             |
| pyrite                  | FeS₂           | 6.5      | 5             | Péntek et al. (2008)                    | yes                          | yes                                 | yes                              |             |
| pyrrhotite              | Fe₁₋ₓS        | 3.5-4    | 4.58 - 4.65   | Péntek et al. (2008)                    | no                           | yes                                 | no                               |             |
| sphalerite              | (Zn,Fe,Cd)S   | 3.5-4    | 3.9 - 4.2     | Péntek et al. (2008)                    | yes                          | no                                  | no                               |             |
| tetradymite             | Bi₂TeS       | 1.5-2    | 7.2 - 7.9     | Péntek et al. (2008)                    | no                           | no                                  | no                               |             |
| malyshkovite           | PdCuBi₂S₃     | not reported | not reported | Kjarsgaard & Ames (2010)               | no                           | no                                  | no                               |             |
| violarite               | (Fe,Ni)₂S₂     | 4.5-5.5  | 4.5 - 4.8     | Péntek et al. (2008)                    | no                           | no                                  | no                               |             |
| wittichenite            | Cu₄Bi₂S₄     | 2.5      | 6.3 - 6.7     | Péntek et al. (2008)                    | no                           | no                                  | no                               |             |
| **Oxides and hydroxides** |               |          |               |                                        |                              |                                     |                                  |             |
| cassiterite             | SnO₂           | 6-7      | 6.8 - 7       | Péntek et al. (2008)                    | no                           | no                                  | no                               |             |
| magnetite               | Fe₂O₄         | 5.5-6    | 5.1 - 5.2     | Péntek et al. (2008)                    | yes                          | yes                                 | yes                              |             |
| malachite               | Cu₂CO₃(OH)₂   | 3.5-4    | 3.6 - 4       | Péntek et al. (2008)                    | no                           | yes                                  | no                               |             |
| hematite                | Fe₂O₃         | 6.5      | 5.3           | Péntek et al. (2008)                    | no                           | no                                  | yes                              |             |
| goethite                | FeO(OH)₂      | 5-5.5    | 3.3 - 4.3     | Péntek et al. (2008)                    | no                           | yes                                 | yes                              |             |
| jarosite                | KFe₂(SO₄)₂(OH)₆ | 2.5-3.5 | 2.9 - 3.3     | Péntek et al. (2008)                    | no                           | yes                                  | no                               |             |
| **Selenides**           |               |          |               |                                        |                              |                                     |                                  |             |
| bohdanowiczite          | AgBi₂Se₂      | 3        | 7.87          | Péntek et al. (2008)                    | no                           | no                                  | no                               |             |
| clausenthalite          | PbSe          | 2.5      | 7.6 - 8.8     | Péntek et al. (2008)                    | no                           | no                                  | no                               |             |
| naumannite              | Ag₂Se        | 2.5      | 6.5 - 6       | Péntek et al. (2008)                    | no                           | no                                  | no                               |             |
| **Tellurides**          |               |          |               |                                        |                              |                                     |                                  |             |
| hessite                 | Ag₂Te        | 1.5-2    | 7.2 - 7.9     | Péntek et al. (2008)                    | no                           | no                                  | no                               |             |
| kawazulite              | Bi₂(Te₂Se₂)   | 1.5      | 7.79          | Ames et al. (2007)                      | no                           | no                                  | no                               |             |
| kotulskite              | Pd(Te₂Bi)    | 4-4.5    | 8.26          | Péntek et al. (2008)                    | no                           | no                                  | no                               |             |
| melonite                | NiTe₂        | 1-1.5    | 7.3           | Péntek et al. (2008)                    | no                           | no                                  | no                               |             |
| Pd-melonite             | (N₁-Pd)Te₂    | not reported | not reported | Ames et al. (2007)                      | no                           | no                                  | no                               |             |
| merenskyite             | Pd₂Te₂       | 2-3      | 9.14          | Péntek et al. (2008)                    | no                           | no                                  | no                               |             |
| michenerite             | PdBi₂Te      | 2.5      | 9.5           | Péntek et al. (2008)                    | yes                          | no                                  | no                               |             |
| moncheite               | (Pt,Pd)Te₂    | 2-3      | 10            | Péntek et al. (2008)                    | no                           | no                                  | no                               |             |
| sopchite                | Ag₂Pd₁Te₄    | 3.5      | 9.95          | Péntek et al. (2008)                    | no                           | no                                  | no                               |             |
| tellurobismuthite       | Bi₂Te₂       | 1.5-2    | 7.82          | Péntek et al. (2008)                    | no                           | yes                                 | no                               |             |
| volynskyite             | Ag₂Bi₂Te     | 2.5-3    | 8.01          | Ames et al. (2007)                      | no                           | yes                                  | no                               |             |
| **Other precious minerals** |             |          |               |                                        |                              |                                     |                                  |             |
| gold                    | Au            | 2.5-3    | 12.5-15       | Mealin (2005)                          | no                           | yes                                  | yes                              |             |
| electrum                | Au₃Ag₄        | 2.5-3    | 12.5-15       | Ames et al. (2007)                      | no                           | yes                                 | yes                              |             |
| native silver           | Ag            | 2.5-3    | 10-11         | Ames et al. (2007)                      | no                           | yes                                  | no                               |             |
| sperrylite              | PtAs₂        | 6-7      | 10.58         | Péntek et al. (2008)                    | no                           | yes                                  | yes                              |             |

Table 1. Summary of ore mineralogy for the Broken Hammer Cu-(Ni)-PGE deposit (modified from Ames et al. 2007; data from Mealin 2005; Watkinson et al. 2005; Péntek et al. 2008; Kjarsgaard & Ames, 2010).
| Sample Number | Material Interpretation | Distance (m) from mineralization | sphalerite grains in pan conc | gold grains in pan conc | pyrite grains | Au ppb (FA) | Pt ppb (FA) | Pd ppb (FA) | Cu ppm | Ni ppm | Ag ppb |
|---------------|-------------------------|----------------------------------|-------------------------------|-------------------------|--------------|------------|------------|-------------|--------|--------|--------|
| 06-MPB-010    | gossan mineralization    | 0                                | 59                            | 178                     | ~80,000      | 0          | 0          |             |        |        |        |
| 06-MPB-011    | gossan mineralization    | 0                                | 54                            | 33                      | ~500,000     | 0          | 0          |             |        |        |        |
| 06-MPB-02     | Sudbury breccia proximal to mineralization | 0                               | 0                             | 0                       | 64           | 0          | 1          | 62          |        |        |        |
| 06-MPB-04     | Sudbury breccia proximal to mineralization | 0                               | 0                             | 0                       | 10           | 0          | 0          |            |        |        |        |
| 06-MPB-06     | quartz monzonite proximal to mineralization | 1.0                             | 0                             | 0                       | 1            | 62         |            |             |        |        |        |
| 06-MPB-07     | amphibolite proximal to mineralization | 6.0                             | 0                             | 30                      | 5            | 0          |            |             |        |        |        |
| 06-MPB-08     | gabbro proximal to mineralization | 25.0                            | 0                             | 0                       | 0            | 625        |            |             |        |        |        |
| 06-MPB-11     | diabase proximal to mineralization | 50.0                            | 0                             | 0                       | 0            | 338        |            |             |        |        |        |
| 06-MPB-12     | amphibolite proximal to mineralization | 75.0                             | 0                             | 0                       | 0            | 935        |            |             |        |        |        |
| 06-MPB-13     | Sudbury breccia proximal to mineralization | 85.0                             | 0                             | 0                       | 0            | ~2000      |            |             |        |        |        |
| 06-MPB-16     | massive chalcopyrite mineralization | 0.0                             | ~2000                         | 0                       | >500,000     | 0          |            |             |        |        |        |

95th percentile reported by Bajc & Hall (2000)  
NR 25 NR NR 30 2.8 3.2 193 97 500

Background defined using samples 06-MPB-001,-002,-003  
NR 28 0 70

Table 2. Abundance of selected indicator minerals in bedrock samples normalized to 1 kg sample mass of <2 mm material and till samples normalized to 10 kg sample mass of <2 mm table feed.
Table 3. Number and size of largest dimension of gold grains recovered from: A) gossan sample 06-MPB-010, and B) till samples. Number and size of largest dimension of sperrylite grains recovered from: C) gossan sample 06-MPB-010, and D) till samples.

### A) gold grains in gossan sample 06-MPB-010

| Size (µm) | 10 | 15 | 25 | 50 | 75 | 100 | 125 | 150 |
|----------|----|----|----|----|----|-----|-----|-----|
|          | 40 | 0  | 0  | 0  | 0  | 0   | 0   | 0   |
|          | 79 | 87 | 0  | 0  | 0  | 0   | 0   | 0   |
|          | 53 | 21 | 0  | 0  | 0  | 0   | 0   | 0   |
|          | 8  | 4  | 2  | 0  | 0  | 0   | 0   | 0   |
|          | 1  | 0  | 0  | 0  | 0  | 0   | 0   | 0   |

N=299
97% of grains 50 µm or less

### B) gold grains in till samples

| Size (µm) | 10 | 15 | 25 | 50 | 75 | 100 | 125 | 150 | 175 | 200 |
|----------|----|----|----|----|----|-----|-----|-----|-----|-----|
|          | 41 | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   | 0   |
|          | 0  | 22 | 0  | 0  | 0  | 0   | 0   | 0   | 0   | 0   |
|          | 130| 180| 0  | 0  | 0  | 0   | 0   | 0   | 0   | 0   |
|          | 145| 53 | 0  | 0  | 0  | 0   | 0   | 0   | 0   | 0   |
|          | 6  | 58 | 10 | 0  | 0  | 0   | 0   | 0   | 0   | 0   |
|          | 17 | 11 | 2  | 0  | 0  | 0   | 0   | 0   | 0   | 0   |
|          | 3  | 4  | 3  | 0  | 0  | 0   | 0   | 0   | 0   | 0   |
|          | 2  | 4  | 0  | 1  | 0  | 0   | 0   | 0   | 0   | 0   |
|          | 0  | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   | 0   |
|          | 1  | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   | 0   |
|          | 0  | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   | 0   |
|          | 1  | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   | 0   |

N=695
93% of grains 75 µm or less

### C) sperrylite grains in gossan

| Size (µm) | 100 |
|----------|-----|
|          | 0   |
|          | 0   |
|          | 0   |
|          | 100  |

N=100
100% of sperrylite grains
100 µm

### D) sperrylite grains in till samples

| Size (µm) | 100 |
|----------|-----|
|          | 31  |
|          | 951 |
|          | 19  |
|          | 12  |

N=1013
94% of sperrylite grains
50 µm or less
Table 4. Bulk modal analysis of the various fraction splits from the <0.25 mm fraction as determined by MLA.

| Mineral                       | 180-250 µm | 125-180 µm | 75-125 µm | 45-75 µm | <45 µm non-mag |
|-------------------------------|------------|------------|-----------|-----------|----------------|
|                               | Vol. %     | Wt. %      | Vol. %    | Wt. %     | Vol. %         |
| Post sieving mass (g)         | 6.09       | 9.46       | 16.13     | 8.97      | 1.42 g         |
| HS concentrate mass (g)       | 0.11       | 0.7        | 0.5       | 0.1       | 0.1            |
| Rutile                        | 1.92       | 1.75       | 0.68      | 0.56      | 0.26           |
| Ti_Magnetite                  | 1.13       | 1.19       | 1.58      | 1.50      | 1.72           |
| Fe_Oxides                     | 47.57      | 52.95      | 62.58     | 62.56     | 56.25          |
| Ilmenite                      | 14.29      | 14.27      | 7.34      | 6.77      | 5.45           |
| Chromite                      | 0.50       | 0.51       | 0.15      | 0.13      | 0.11           |
| Fe-Ti-Cr oxides total        | 65.41      | 70.67      | 72.55     | 71.52     | 63.83          |
| Calcite                       | 0.01       | 0.01       | 0.01      | 0.01      | 0.01           |
| Quartz                        | 2.52       | 1.42       | 1.74      | 0.88      | 0.97           |
| K-Feldspar                    | 0.27       | 0.14       | 0.12      | 0.06      | 0.08           |
| Albite                        | 0.44       | 0.25       | 0.19      | 0.09      | 0.18           |
| Talc                          | 0.00       | 0.00       | 0.00      | 0.00      | 0.00           |
| Fe_Chlorite                   | 0.97       | 0.53       | 0.28      | 0.14      | 0.14           |
| Mg_Chlorite                   | 0.27       | 0.15       | 0.06      | 0.03      | 0.04           |
| Biotite                       | 0.79       | 0.50       | 0.55      | 0.31      | 0.30           |
| Muscovite                     | 0.90       | 0.54       | 0.77      | 0.41      | 0.51           |
| Qtz & lights total            | 6.45       | 3.69       | 3.81      | 1.97      | 2.27           |
| Cassiterite                   | 0.00       | 0.00       | 0.26      | 0.34      | 0.30           |
| Epidote                       | 1.79       | 1.29       | 0.99      | 0.06      | 0.03           |
| Olivine                       | 0.03       | 0.02       | 0.00      | 0.00      | 0.00           |
| Hedenbergite_Cpx              | 0.09       | 0.07       | 0.00      | 0.00      | 0.00           |
| Hypersthene_Opx               | 4.90       | 3.21       | 0.67      | 0.39      | 0.01           |
| Amphibole                     | 3.04       | 1.90       | 0.12      | 0.07      | 0.06           |
| Garnet                        | 7.23       | 6.56       | 2.55      | 2.08      | 0.49           |
| Apatite                       | 0.60       | 0.41       | 0.24      | 0.15      | 0.33           |
| Monazite                      | 0.88       | 0.96       | 1.51      | 1.48      | 1.08           |
| Dingdaohengite_Ce             | 0.00       | 0.00       | 0.09      | 0.09      | 0.00           |
| Gorceixite                    | 0.04       | 0.03       | 0.01      | 0.00      | 0.01           |
| Allanite                      | 0.05       | 0.04       | 0.01      | 0.00      | 0.01           |
| Brannerite                    | 0.02       | 0.02       | 0.00      | 0.00      | 0.00           |
| Cpx, Opx, Amph & accessories  | 20.58      | 15.93      | 6.07      | 5.00      | 3.03           |
| Baddeleyite                   | 0.00       | 0.00       | 0.00      | 0.00      | 0.00           |
| Zircon                        | 6.18       | 8.42       | 17.03     | 20.98     | 30.44          |
| Zinc & baddeleyite total      | 6.18       | 8.42       | 17.03     | 20.98     | 30.44          |
| Chalcopryte                   | 0.76       | 0.67       | 0.14      | 0.12      | 0.00           |
| Bornite                       | 0.00       | 0.00       | 0.01      | 0.01      | 0.00           |
| Pentlandite                   | 0.00       | 0.00       | 0.00      | 0.00      | 0.00           |
| Pyrrhotite                    | 0.00       | 0.00       | 0.00      | 0.00      | 0.00           |
| Pyrite                        | 0.39       | 0.41       | 0.14      | 0.14      | 0.07           |
| Arsenopyrite                  | 0.00       | 0.00       | 0.00      | 0.00      | 0.00           |
| Galena                        | 0.00       | 0.00       | 0.00      | 0.00      | 0.00           |
| Sulphides total               | 1.15       | 1.08       | 0.29      | 0.27      | 0.07           |
| Gold/Electrum                 | 0.00       | 0.00       | 0.00      | 0.00      | 0.10           |
| Sperrylite                    | 0.03       | 0.06       | 0.07      | 0.15      | 0.18           |
| Pd_Oxide?                     | 0.00       | 0.00       | 0.00      | 0.00      | 0.00           |
| Au & PGM total                | 0.03       | 0.06       | 0.07      | 0.15      | 0.28           |
| Fe_Sulphate                   | 0.00       | 0.00       | 0.00      | 0.00      | 0.00           |
| Fe_Ox_Sulphate?               | 0.07       | 0.04       | 0.01      | 0.04      | 0.00           |
| Altered sulphides total       | 0.07       | 0.04       | 0.01      | 0.01      | 0.00           |
| Other                         | 0.13       | 0.11       | 0.17      | 0.10      | 0.08           |
Table 5. Particle statistics for precious metal grains detected by mineral liberation analysis of the five hydroseparation concentrates of till sample 06-MPB-012 overlying mineralized bedrock.

| Fraction           | Number of particles |
|--------------------|---------------------|
|                    | Sperrylite | Electrum/Gold | Michenerite | Bi Moncheite | Merenskyite |
| 180-250 µm non-magnetic | 2          | 0            | 1           | 1            | 1           |
| 125-180 µm non-magnetic | 9          | 0            | 0           | 1            | 0           |
| 75-125 µm non-magnetic   | 10         | 3            | 0           | 0            | 0           |
| 45-75 µm non-magnetic   | 39         | 12           | 0           | 0            | 0           |
| <45 µm non-magnetic     | 23         | 8            | 0           | 0            | 0           |