Natural Resources Canada
Ressources naturelles Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8384

Indicator mineral data for till samples from the Broken Hammer Cu-Ni-PGE-Au deposit, North Range, Sudbury Structure, Ontario

M.B. McClenaghan, I.M. Kjarsgaard, D.E. Ames, and D. Crabtree

2018

Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8384

Indicator mineral data for till samples from the Broken Hammer Cu-Ni-PGE-Au deposit, North Range, Sudbury Structure, Ontario

M.B. McClenaghan[1], I.M. Kjarsgaard[2], D.E. Ames[3], and D. Crabtree[4]

[1]Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario K1A 0E8
[2]Consulting Mineralogist/Petrologist, 15 Scotia Place, Ottawa, Ontario K1S 0W2
[3]Retired, Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario K1A 0E8
[4]Geoscience Laboratories, 933 Ramsey Lake Road, Sudbury, Ontario P3E 6B5

2018

Permanent link: https://doi.org/10.4095/308118

Recommended citation
McClenaghan, M.B., Kjarsgaard, I.M., Ames, D.E., and Crabtree, D., 2018. Indicator mineral data for till samples from the Broken Hammer Cu-Ni-PGE-Au deposit, North Range, Sudbury Structure, Ontario; Geological Survey of Canada, Open File 8384, 1 .zip file. https://doi.org/10.4095/308118

TABLE OF CONTENTS

Appendices

Figures

Tables

Indicator mineral data for till samples from the Broken Hammer Cu-Ni-PGE-Au deposit, North Range, Sudbury Structure, Ontario

M.B. McClenaghan[1], I.M. Kjarsgaard[2], D.E. Ames[3],and D. Crabtree[4]

[1]Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario K1A 0E8
[2]Consulting Mineralogist/Petrologist, 15 Scotia Place, Ottawa, Ontario K1S 0W2
[3]Retired, Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario K1A 0E8
[4]Geoscience Laboratories, Ontario Geological Survey, 933 Ramsey Lake Road, Sudbury, Ontario P3E 6B5

INTRODUCTION

Few indicator mineral case studies have been conducted to demonstrate or test indicator minerals as a viable exploration method for Ni-Cu-PGE deposits in glaciated terrain. To address this knowledge gap, the Geological Survey of Canada (GSC), through its Targeted Geoscience Initiative 3 (TGI-3) program, collected and analyzed a suite of bedrock and till samples from around the Broken Hammer Cu-(Ni)-PGE deposit in the North Range of the Sudbury Structure, northeastern Ontario (Fig. 1).

The Broken Hammer deposit was chosen as a magmatic-Ni-Cu-PGE indicator mineral test site for a number of reasons: (1) the deposit was known to contain coarse-grained platinum group minerals; (2) the bedrock and surficial geology of the area were well known; (3) the deposit subcrops and thus was exposed to glacial erosion; (4) the study area was easily accessible by road; and (5) the deposit was located north of the Sudbury Structure and thus up-ice of the major Ni-Cu-PGE deposits, mines, and smelters within the Sudbury region. There were two specific objectives of the research project: 1) to determine the indicator mineral signatures that are indicative of magmatic-Ni-Cu-PGE mineralization; and 2) to establish practical methods that can be routinely applied in exploration for recovery and identification of indicator minerals from the glacial sediments. The purpose of this open file is to report and discuss indicator mineral data for till samples collected from the deposit area. Several previous publications have reported other data for the Broken Hammer case study: raw indicator mineral lab data for bedrock and till samples (McClenaghan and Ames, 2013), indicator mineral data for bedrock samples (McClenaghan et al., in press), and till geochemical data (McClenaghan et al., 2014).

LOCATION

The Broken Hammer deposit is located 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 and longitude 82°57’55” W (Fig. 1) and can be 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 Sudbury world-class Ni-Cu mining district is associated with the 1.85 Ga Sudbury Igneous Complex (SIC), an elliptical body with offset dykes that straddles the boundary between the Archean Superior Province in the north and the Paleoproterozoic Southern Province to the south (Fig. 2). Over 1.7 billion tonnes of Ni, Cu, Co, Pt, Pd, Au, and Ag ore (Lydon, 2007) have been mined from this exceptional mining district, which remains a vital exploration target. The polymetallic ore is hosted within one of Earth’s largest preserved impact craters, the Sudbury Structure.

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 episodes (Nipissing, Sudbury and Grenville dyke swarms), with minor felsic episodes (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 (Card, 1994; Ames et al., 2005). These rocks were strongly affected by the shock and thermal effects of the Sudbury impact at 1850 Ma.

The shocked and brecciated basement rocks (Sudbury breccia unit) and melt rocks (Sudbury Igneous Complex) control, host, and significantly contributed to the formation of the ores (Ames et al., 2006). The igneous rocks of the Sudbury Structure form the 60 x 30 km elliptical outline of the SIC, together with radial and concentric, quartz diorite dykes in offset structures (Fig. 2). Sudbury breccia, in the stratigraphic and structural footwall to the SIC, consists of country rock fragments in a cataclastic to pseudotachylitic

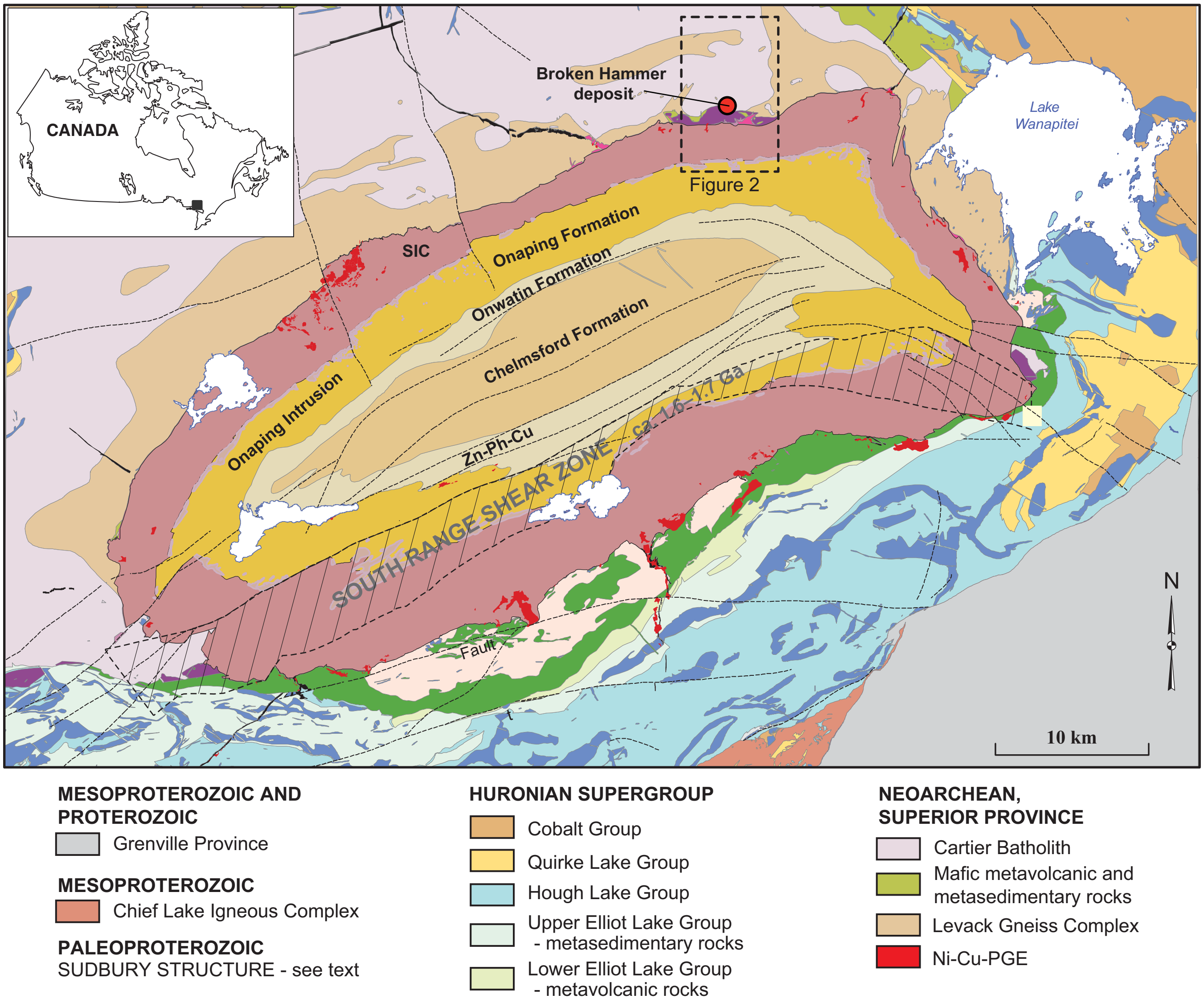


Figure 1. Location of the study area in the Sudbury Basin in northeastern Ontario (modified from Ames and Farrow 2007).

matrix and form randomly oriented stringers and large zones or "belts" of breccia found up to 200 km from the base of the Sudbury Igneous Complex (SIC; Speers, 1957; O'Callaghan et al., 2016a,b). Sudbury breccia represents an important economic target as a host to Sudbury's largest Ni-Cu-PGE deposit (Frood-Stobie) and Cu-PGE and PGE-only "footwall deposits".

Sudbury Ni-Cu-PGE ore deposits

Some of the Sudbury area Ni-Cu-PGE mines have operated for over a century, whereas new ore deposits and ore types, discovered as recently as 2004, are already in production or are in the process of being developed (i.e. advanced prospects). Sudbury Ni-Cu contact-type deposits are widely accepted to be of magmatic origin, having formed during differentiation of the SIC followed by sulphide segregation and subsequent collection in topographic lows or "embayments" at the base of the SIC. The origin of the Cu-Ni-PGE systems is controversial: both magmatic and hydrothermal processes having been supported in the literature. More recently, a magmatic-hydrothermal origin was postulated whereby initial magmatic differentiation of the sulphide liquid resulted in the formation of a residual sulphide liquid enriched in Cu, Pt, Pd, and Au. This liquid was then remobilized into structural pathways or permeable zones of brecciated country rock or Sudbury breccia in the footwall of the SIC. The recent division of footwall Cu-(Ni)-PGE deposits into high-sulphide, (sharp-walled vein) and low-sulphide (PGE-rich) systems based on large geochemical mine databases (Farrow et al., 2005), instigated a series of comprehensive geoscience studies to determine the characteristics, origin, mode of transport, and timing of the low-sulphide PGE-rich mineralization relative to the high-sulphide, largely magmatic veins. Later hydrothermal mobilization resulted in redistribution of base and precious metals, modification of the ore composition, and

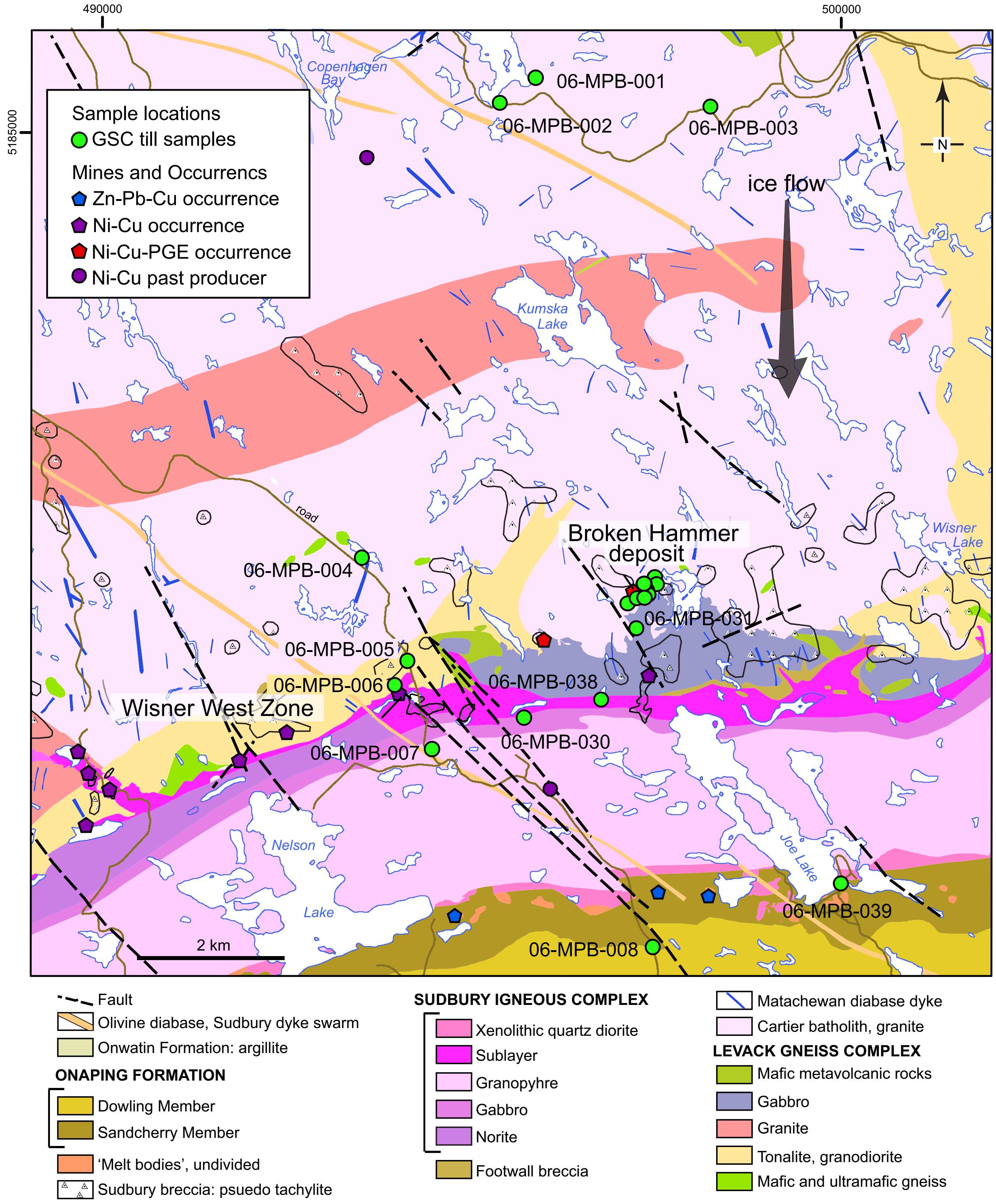


Figure 2. Regional bedrock geology map (Ames et al., 2005) with the location of till samples collected in 2006 by the Geological Survey of Canada around the Broken Hammer deposit across the North Range.

the formation of Cl-rich alteration haloes. Fluid inclusion stable isotope evidence suggests ore metal transport and redistribution involved mixing between regional groundwater and a metal-rich ore fluid with a magmatic component to form a metal-enriched brine that partitioned, causing Au precipitation and phase separation of Cu, Au, Ag, and Bi into a CH_4-bearing fluid that further dispersed Cu, Pt, Au, Ag, and Bi (Farrow et al., 1994; Hanley et al., 2005, 2006).

Footwall-hosted Cu-PGE deposits are a relatively new resource in the Sudbury camp, other than the earlier discoveries in the Onaping-Levack area that included the McCreedy deposits and the Strathcona Deep Copper zone (Coats and Snajdr, 1984). Rising metal prices triggered an exploration surge for footwall deposits in the Sudbury Camp due to their high copper and precious metal content. This resulted in the discovery of numerous PGE-rich mineralized zones, including the hybrid Broken Hammer zone (Péntek et al., 2008). Cu-Ni-PGE deposits and occurrences studied by the GSC include Creighton 403, Creighton Deeps, Barnett, McCreedy East 153 zone, Victor Deep, Levack Footwall, McCreedy West PM zone, Segway, and Broken Hammer Cu-PGE (Ames et al., 2007, 2013a).

Local bedrock geology

The Broken Hammer deposit and Wisner west zone are situated on the North Range of the Sudbury Structure in Wisner Township, 1.5 km north of the SIC contact with footwall rocks of the Archean Joe Lake gabbro and/or granite and quartzo-feldspathic and mafic gneiss of the Levack Gneiss Complex and Cartier batholith (Fig. 2). Numerous contact Ni-Cu mineralized zones occur along the base of the moderately (30ºS) south-dipping SIC contact (i.e. WD-13, WD-16, Rapid River; Ames et al., 2005). The Wisner west zone is situated in the footwall to a 12 km-long embayment in the SIC (Bowell embayment) that is bounded to the west by the Foy offset and to the east by the Joe Lake intrusion. The Wisner west area is dominated by felsic and mafic gneiss with plagioclase-porphyritic diabase dykes of probable Matachewan origin. Zones of Sudbury breccia host the Cu-PGE disseminations and veinlets are commonly altered to quartz-epidote-carbonate-chlorite rich assemblages.

Two outcrop areas stripped by Vale-Lonmin at the Wisner west occurrence exposed a few sulphide veinlets, quartz-carbonate, epidote-quartz, and disseminations hosted in Sudbury breccia (pseudotachylite). The decoupling of platinum group element (PGE) grades from the abundance of chalcopyrite is what characterizes this low-sulphide high-PGE mineralization at Wisner west (Ames and Kjarsgaard, 2013).

Approximately 3.5 km to the west of Wisner west is the Broken Hammer Cu-Ni-PGE-Au deposit, situated 1.3 km from the base of the SIC along the northern margin of the Joe Lake gabbroic intrusion. It is a shallow surface zone of vein- and vein stockwork-hosted mineralization (Fig. 3) within Sudbury breccia developed in Neoarchean quartz monzonite, Levack Gneiss Complex (Peterson et al., 2004; Péntek et al., 2006, 2008). The Broken Hammer deposit was discovered in 2003 by Wallbridge Mining Company Ltd. through surface prospecting and sampling for Cu-Ni-PGE mineralization sulphide veins (Doran et al., 2012). This report presents the results of mineralogical studies of till samples collected from an outcrop area that was stripped and sampled by the GSC in 2006.

The main 2 to 120 cm-wide en echelon chalcopyrite vein named 'Big Boy' (Fig. 4), which was uncovered by stripping the outcrop, is dominated by chalcopyrite-magnetite-millerite with numerous trace and rare precious metal minerals such as telluride, bismuthide, selenide, and stannide (Table 1). A thin (cms) post-glacial gossan, whose location is indicated in Figure 3, was developed on a small part of the chalcopyrite vein and was exposed on the stripped bedrock surface in 2006 (Fig. 5). This gossan contains abundant sperrylite, as well as chalcopyrite and other minerals (Fig. 6; Se-galena, cassiterite, kotulskite, merenskyite, electrum, arsenopyrite, and native silver) in a goethite matrix. Trace elements in the mineral assemblages in the weathered sulphide include Pd-Pt-Sn-Pb-Au-Ag-As-Bi-Te, which are reflected in the sulphide ore lithogeochemistry (Ames et al., 2007; Péntek et al., 2008). Epidote is a common alteration mineral in the local area.

In 2011, a 30,000 tonne bulk sample was taken from Broken Hammer, creating an open pit and removing much of the till and bedrock that was sampled by the GSC in 2006. New exposures in the pit revealed a "super", high-grade sperrylite zone comprising a hydrothermal assemblage of coarse epidote-quartz-sperrylite with world-class sperrylite crystals as large as 15 mm (Wilson, 2012; Ames et al., 2013b). Positive results from this initial bulk sample led to a prefeasibility study and resource estimates.

Open pit mining at Broken Hammer started in 2014 and from its opening until its closure in October 2015, 10,265 tonnes of Cu concentrates were delivered to a Cu smelter with an average grade of 24.15% Cu and 60.4 g/t PGM (18.6 g/t Pt, 34.5 g/t Pd and 7.3 g/t Au). In addition, 180 tonnes of high-grade gravity concentrates were shipped to a PGM smelter in Europe having an average PGM grade of 1,924 g/t (1,551 g/t Pt, 145 g/t Pd, and 228 g/t Au) (Wallbridge Mining Company Ltd., 2018).

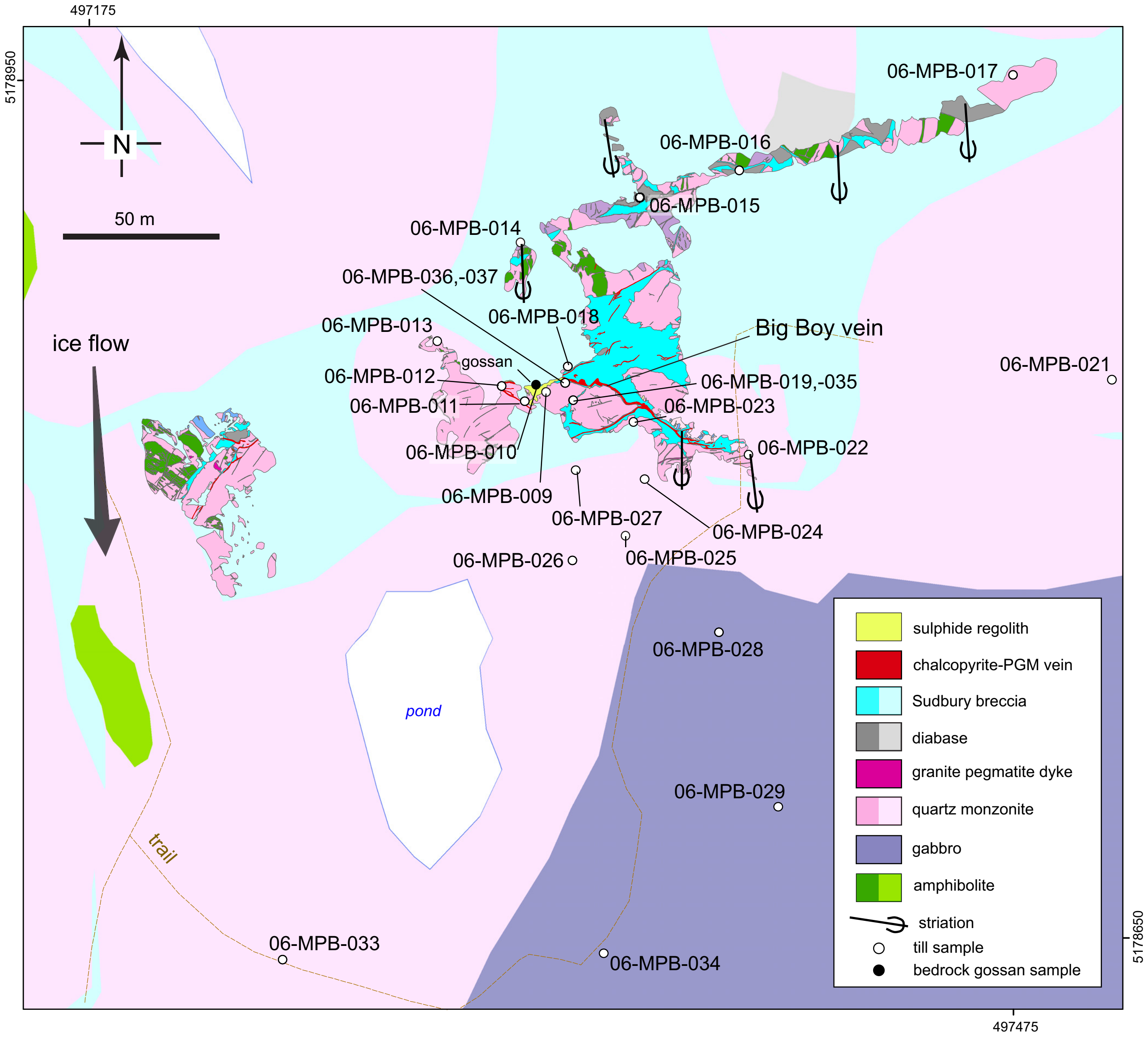


Figure 3. Detailed bedrock geology of the stripped bedrock area (Peterson et al., 2004), superimposed on the regional bedrock geology (Ames et al., 2005). The locations of the bedrock samples collected proximal to the Big Boy chalcopyrite vein by the Geological Survey of Canada are also shown (white dots). The detailed bedrock geology, which was exposed in 2006 by stripping on the Broken Hammer property, is shown by darker shades of the corresponding lighter colour of the regional geology.

Figure 4. Colour photograph of the Big Boy chalcopyrite vein exposed in the pre-2007 stripped area at the Broken Hammer deposit. cpy = chalcopyrite.

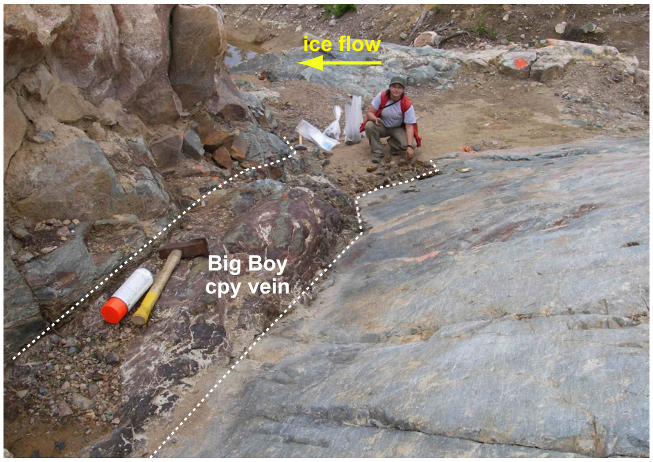


Table 1. List of the ore minerals present in the Broken Hammer Cu-(Ni)-PGE deposit and in till overying and down-ice of the deposit (modified from Ames et al., 2007; data from Mealin, 2005; Watkinson et al., 2005; Péntek et al., 2008; Kjarsgaard and Ames, 2010).

Mineral	Formula	Hardness*	Density*	At Broken Hammer, Identified by others	Identified in Broken Hammer PTS this study	Identified in bedrock HMC this study	Identified in till HMC this study
Sulphide minerals							
arsenopyrite	$FeAsS$	5	6.07	Ames et al. (2007)	no	no	no
bornite	Cu_5FeS_4	3	4.9–5.3	Péntek et al. (2008)	yes	no	no
chalcocite	Cu_2S	2.5–3	5.5–5.8	no	no	yes	no
chalcopyrite	$CuFeS_2$	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
crerarite	$PtBi_3S_{4-x}$	3	not reported	Péntek et al. (2008)	no	no	no
emplectite	$CuBiS_2$	2	6.3–6.5	Ames et al. (2007)	no	no	no
galena (Se)	$Pb(S,Se)$ ±Bi,Ag	2.5	7.2–7.6	Ames et al. (2007)	no	galena	no
millerite	NiS	3–3.5	5.5	Péntek et al. (2008)	no	yes	no
pentlandite	$(Fe,Ni,Co)_9S_8$	3.5–4	4.6–5	Péntek et al. (2008)	no	no	no
polydymite	Ni_2S_4	4.5–5.5	4.5–4.8	Kjarsgaard & Ames (2010)	no	no	no
pyrite	FeS_2	6.5	5	Péntek et al. (2008)	yes	yes	yes
pyrrhotite	$Fe_{1-x}S$	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	Bi_2Te_2S	1.5–2	7.2–7.9	Péntek et al. (2008)	no	no	no
malyshevite	$PdCuBiS_3$	not reported	not reported	Kjarsgaard & Ames (2010)	no	no	no
violarite	$(Fe,Ni)_3S_4$	4.5–5.5	4.5–4.8	Péntek et al. (2008)	no	no	no
wittichenite	Cu_3BiS_3	2.5	6.3–6.7	Péntek et al. (2008)	no	no	no
Oxide and hydroxide minerals							
cassiterite	SnO_2	6–7	6.8–7	Péntek et al. (2008)	no	no	no
magnetite	$FeFe_2O$	5.5–6	5.1–5.2	Péntek et al. (2008)	yes	yes	yes
malachite	$Cu_2CO_3(OH)_2$	3.5–4	3.6–4	no	no	yes	no
hematite	Fe_2O_3	6.5	5.3	Péntek et al. (2008)	no	yes	yes
goethite	$FeO(OH)$	5–5.5	3.3–4.3	no	no	yes	yes
jarosite	$KFe_3(SO4)_2(OH)_6$	2.5–3.5	2.9–3.3	no	no	yes	no
Selenide minerals							
bohdanowiczite	$AgBiSe_2$	3	7.87	Péntek et al. (2008)	no	no	no
clausthalite	$PbSe$	2.5	7.6–8.8	Péntek et al. (2008)	no	no	no
naumannite	Ag_2Se	2.5	6.5–8	Péntek et al. (2008)	no	no	no
Telluride minerals							
hessite	Ag_2Te	1.5–2	7.2–7.9	Péntek et al. (2008)	no	no	no
kawazulite	$Bi_2(Te,Se,S)_3$	1.5	7.79	Ames et al. (2007)	no	no	no
kotulskite	$Pd(Te,Bi)$	4–4.5	8.26	Péntek et al. (2008)	no	no	no
melonite	$NiTe_2$	1–1.5	7.3	Péntek et al. (2008)	no	no	no
Pd-melonite	$(Ni,Pd)Te_2$	not reported	not reported	Ames et al. (2007)	no	no	no
merenskyite	$(Pd)(Te,Bi)_2$	2–3	9.14	Péntek et al. (2008)	no	no	no
michenerite	$PdBiTe$	2.5	9.5	Péntek et al. (2008)	no	yes	no
moncheite	$(Pt,Pd)(Te,Bi)_2$	2–3	10	Péntek et al. (2008)	no	no	no
sopcheite	$Ag_4Pd_3Te_4$	3.5	9.95	Péntek et al. (2008)	no	no	no
tellurobismuthite	Bi_2Te_3	1.5–2	7.82	Péntek et al. (2008)	no	yes	no
volynskite	$AgBiTe_2$	2.5–3	8.0	Ames et al. (2007)	no	no	no
Other precious minerals							
electrum	$Au_{65}Ag_{35}$	2.5–3	12.5–15	Péntek et al. (2008)	no	yes	yes
gold	Au	2.5–3	16–19.3	Mealin (2005)	no	yes	yes
native silver	Ag	2.5–3	10–11	Ames et al. (2007)	no	no	no
sperrylite	$PtAs_2$	6–7	10.58	Péntek et al. (2008)	no	yes	yes

*data from www.webmineral.com

Figure 5. Colour photographs of sample site 06-MPB-010 showing the post-glacial gossan that developed on the Big Boy chalcopyrite vein that was exposed in a small open pit in 2006: **a)** an overview of the sample site and **(b)** a close-up of honeycomb texture that has developed in the gossan. The sample site is marked by yellow dashed line.

Surficial geology

The Sudbury region was most recently glaciated during the Late Wisconsinan (25,000 to 10,000 years ago), during which time ice of the Labrador Sector of the Laurentide Ice Sheet covered the Sudbury region and generally flowed to the south-southwest (Fig. 7) (Boissoneau, 1968; Bajc, 1997a,b,c; Bajc and Hall, 2000). In the Wisner Township area, till was deposited by ice flowing southward (185–175°). 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 (<0.5–3 m thick), locally-derived, has a silty sand (>50% sand) matrix, is loose, and contains about 10 to 30% clasts. Soil has been developing on the glacial sediments of the North Range since deglaciation, about 10,000 years ago, which has produced a podzolic soil (Barnett and Bajc, 2002).

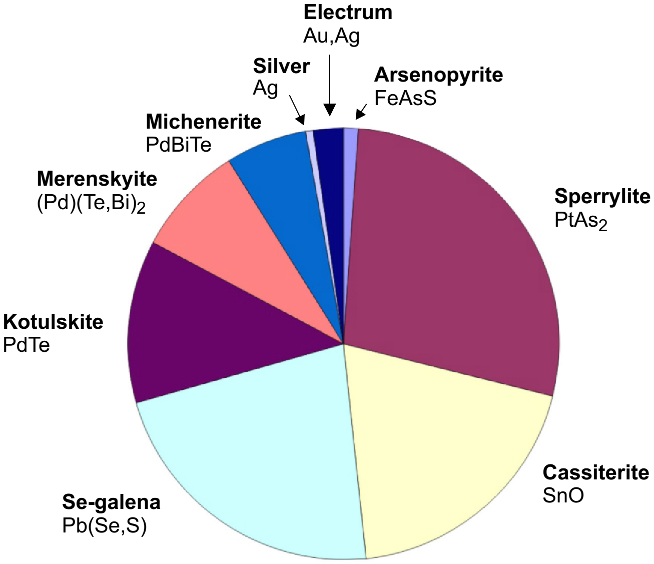


Figure 6. Pie chart illustrating the relative abundance of Pt-Pd-As-Sn minerals in a 1 kg sample of the post-glacial gossan that has developed on the Broken Hammer Big Boy chalcopyrite vein (n = 180 mineral grains; from Ames et al. (2007).

Historically, till sampling has not been a component of mineral exploration in the Sudbury region due to the abundant bedrock outcrop and the widespread surface contamination related to the mining and smelting operations in the Sudbury region over the last 120 years. However, unlike the South Range, the North Range and west end of the Sudbury Structure have thicker and more continuous till cover that masks the underlying bedrock. The widespread till cover in these areas provides an ideal sample medium for drift prospecting. These areas to the west and north are 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.

Bajc and Hall (2000) carried out both a regional-scale till geochemical survey of the North and West ranges in the Sudbury Structure, as well as detailed studies at selected deposits/occurrences, including footwall mineralization on the Barnet property, in support of Ni-Cu-PGE exploration. They demonstrated that till matrix geochemistry is a useful exploration method in the Sudbury region, however, they 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 the Barnet footwall mineralization.

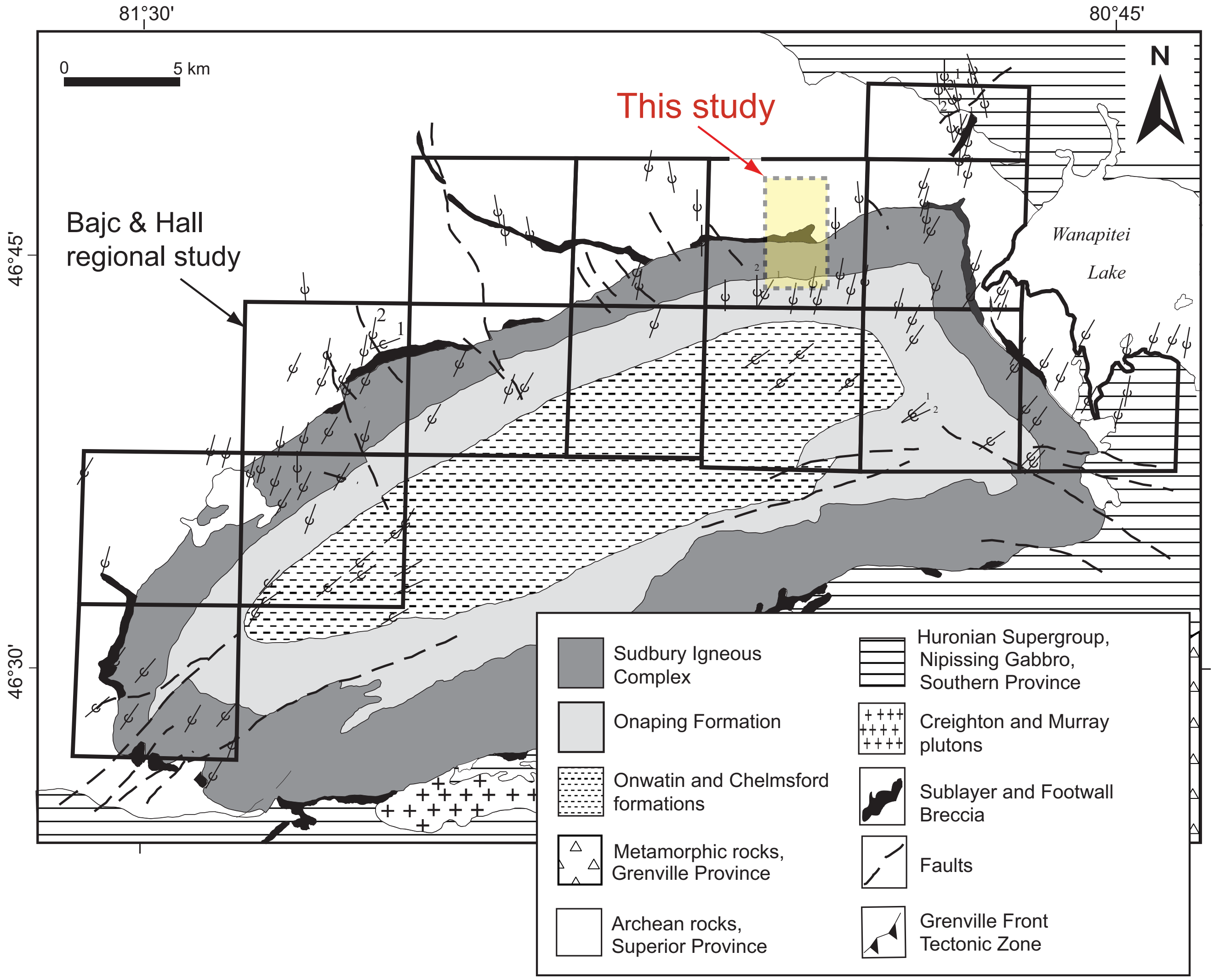


Figure 7. Late Wisconsin regional ice-flow patterns in the Sudbury region (modified from Bajc and Hall, 2000).

METHODS

Field sampling methods

A total of 34 till samples were collected in 2006 (Figs. 2, 3) around the Broken Hammer deposit for indicator mineral and matrix geochemical analyses. Sites included sections exposed along the main stripped bedrock surface containing the Big Boy vein (samples 06-MPB-009, -011, -012, -018, -019, -035, -036, and -037) (Fig. 3), and along associated stripped outcrops or clearings (samples 06-MPB-013 to -017, -020 to -027). Samples were also collected from road cuts between 9 and 600 m south (down-ice) of the deposit (samples 06-MPB-028, -029, and -031 to -034). Samples 06-MPB-005 to -008, -030, -038 and -039 were collected 1.5 to 5 km south of the deposit. Samples 06-MPB-01 to -03 were collected 6 km north of the deposit to establish background till composition. Samples 06-MPB-04 to -07 were collected up-ice (north), overlying, and just down-ice (south) of the Wisner West Cu-PGE deposit (Fig. 3).

A bulk sample (06-MPB-10) of the post-glacial gossan was collected for petrography and to recover heavy minerals to determine mineralogy. Till and gossan sample locations as well as field descriptions are included in Appendix A and individual site photos are reported with the till geochemical data in McClenaghan and Ames (2013). In addition to till sampling, bedrock striations were measured to record the local direction of glacial transport. Striations measured in this study are reported in Appendix A.

Sample processing and indicator mineral recovery

Large till samples (~15 kg) were processed at Overburden Drilling Management Ltd. (ODM), Ottawa, to produce non-ferromagnetic heavy mineral concentrates for picking indicator minerals, details of which can be found in detail in McClenaghan and Ames (2013). First, the samples were disaggregated and sieved to obtain the <2.0 mm material, which was then passed over a shaking table to produce a table pre-concentrate. The pre-concentrate was then micro-panned to recover gold, sulphide, and platinum group minerals (PGM). These panned minerals were examined, counted, and then returned to the sample. The gold and sperrylite grain counts reported in Table 2 are the result of this processing step.

The <2.0 mm pre-concentrate was then further refined using heavy liquid separation in methylene iodide diluted to a specific gravity (SG) of 3.2. The ferromagnetic fraction was removed, 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. These three fractions were then examined for indicator minerals. Chalcopyrite and pyrite grain counts that are reported in Table 2 are the result of this step. Complete listings of indicator mineral data for till samples from this study were initially reported in McClenaghan and Ames (2013).

A selected number of epidote, titanite, rutile, and ilmenite grains were selected for further examination at a later date. These new grain abundances are reported in Appendix B, in the “additional picking” and “Epidote Estimates” worksheets of the raw lab data reported by ODM. Appendix B is an updated version of the ODM data file first reported as Appendix B2 of Open File 7388 (McClenaghan and Ames, 2013).

Electron microprobe analysis

Four mineral grain mount maps are included in Appendix C1. Electron microprobe (EMP) data for grains in the mounts are listed in Appendix C2 to C6. EMP analyses of epidote, apatite, and titanite grains were carried out the GSC, Ottawa. Data were acquired on a Cameca SX-50 microprobe fitted with 4 wavelength-dispersive spectrometers with a take-off angle of 40 degrees. Normal operating conditions were 20 kv accelerating voltage and 10 nA current. Count times were 10 seconds on-peak and 5 seconds off-peak. Standards used were a mixture of natural and synthetic pure metals, simple oxides, and simple compounds. Data reduction was accomplished with a ZAF matrix correction (Armstrong, 1988) using Probe For Windows software. Electron microprobe (EMP) data for epidote, titanite and apatite conducted at GSC Ottawa are listed in Appendix C2, C5, and C6.

Additional microprobe analyses of selected epidote grains were carried out at Carleton University, Ottawa using a four-spectrometer wavelength dispersive CAMECA Camebax. Oxide mienrals were analyzed at 20 kV and 25 to 30 nA sample current with 10 to 20 seconds counting time. Standards used were $MgAl_2O_4$ for Mg and Al, Cr_2O_3 for Cr, MnTi for Mn, $CaSiO_3$ for Si and Ca, $FeTiO_3$ for Ti and Fe, NiO for Ni, $ZnAl_2O_4$ for Zn, and V for V. Silicate minerals were analyzed at 15 kV and 20 nA with counting times of 20 seconds per element. Standards used were $CaSiO_3$ for Si and Ca, $MgAl_2O_4$ for Al, Mg_2SiO_4 for Mg, Fe_2SiO_4 for Fe, Cr_2O_3 for Cr, MnTi for Ti and Mn, NiO for Ni, $KAl_3Si_3O_8$ for K, $NaAl_3Si_3O_8$ for Na, and $ZnAl_2O_4$ for Zn. Overlap corrections were performed using the PAP procedure. Calibrations were checked by analyzing known USNM standards (that were not used for calibration) as samples. Electron microprobe data for epidote produced at Carleton University are listed in Appendix C2.

Axinite EMP analyses was carried out using a Cameca SX-100 Electron Probe Micro Analyzer (EPMA) at the Geoscience Laboratories (Ontario Geological Survey) in Sudbury, Ontario. Major elements were analyzed under normal operating conditions (20 kV and 20 nA). The edited EMP data are listed in Appendix C3. OGS EMP raw data and electron microprobe operating conditions are listed in Appendix C4.

RESULTS

Indicator mineral grain counts for the 0.25–0.5 mm fraction of heavy mineral concentrates of till samples were normalized to a 10 kg sample weight (<2 mm table feed) to allow comparison between samples (Table 2). These normalized results are discussed below and are plotted as proportional dot maps in Appendix D (Maps 1 to 5). Colour photographs of selected indicator minerals grains are included in Figure 8. Results for the Wisner west till samples (06-MPB-04, -05, -06, -07) are listed in the appendices but are not described or discussed below.

Platinum group minerals

Sperrylite ($PtAs_2$) is a platinum group mineral (PGM) that is easily recognizable in pan concentrates by its bright silver white colour (Fig. 8a,b). The background content of sperrylite grains in the pan concentrate fraction of till samples up-ice of the deposit (defined using regional data of Bajc and Hall (2000)) is zero. Till samples proximal to mineralization were found to contain between 0 and 714 sperrylite grains/10 kg in the pan concentrate (Table 2; Appendix D, Map 1). Overlying mineralization, till contains up to 714 sperrylite grains. Between 10 and 50 m down-ice, till contains 10s of grains; between 50 and 250 m down-ice, till contains a few visible sperrylite grains. Sample 06-MPB-031, collected 600 m down-ice, contains 21 sperrylite grains.

Gossan sample 06-MPB-010, also processed by ODM, contained an estimated 100 grains of sperrylite in the pan concentrate as well as 9 grains in the 0.25–0.5 mm heavy mineral fraction. Sperrylite grains in the coarser 0.5–1.0 mm and 1.0–2.0 mm fractions of sample 06-MPB-010 are aggregates of sperrylite + goethite

Table 2. Abundance of selected indicator minerals in till samples examined for this study normalized to 10 kg sample weight of table feed (<2 mm material). Counts reported for gold and sperrylite are for pan concentrates; counts for chalcopyrite, pyrite, and axinite are for the 0.25–0.5 mm heavy mineral fraction. Au, Pt, and Pd were determined by fire assay/ICP-MS; Cu and Ag were determined by aqua regal/ICP-MS.

Location	Sample	Strength of till oxidation	Distance (m) from Broken Hammer mineralization	Direction from Broken Hammer mineralization	Weight <2 mm table feed	Sperrylite grains/ 10 kg	Chalcopyrite grains/10 kg	Gold grains/ 10 kg	Pyrite grains/ 10 kg	Axinite gains/ 10 kg	Au ppb	Pt ppb	Pd ppb	Cu ppm	Ag ppb
background	06-MPB-001	strong	-6000	N	6.7	0	0	12	3	0	3	3.4	3.5	115	25
background	06-MPB-002	strong	-6000	N	7.1	0	0	4	70	0	4	2.5	2.2	152	27
background	06-MPB-003	moderate	-6000	N	10.1	0	0	28	10	0	6	1.5	1.6	56	23
proximal up ice	06-MPB-020	strong	-250	NE	8.8	0	0	11	170	0	2	1.1	1.7	39	14
proximal up ice	06-MPB-021	moderate	-125	NE	10.0	0	0	3	10	0	2	5.3	5.4	166	5
proximal up ice	06-MPB-017	weak	-100	NE	9.8	0	0	2	15	0	2	1.1	0.7	44	3
proximal up ice	06-MPB-014	moderate	-45	N	7.9	0	0	5	51	0	4	2.1	6.5	53	8
proximal up ice	06-MPB-016	strong	-30	NE	10.1	0	0	5	30	0	2	0.7	3.1	36	6
proximal up ice	06-MPB-015	strong	-25	N	9.6	0	0	4	52	0	2	1.0	4.0	108	6
proximal up ice	06-MPB-018	weak	-1	N	8.3	12	145	30	60	0	3	2.7	7.6	324	10
overlying	06-MPB-009	weak	0	N/A	9.4	2	5	3	32	0	5	7.7	20.8	231	15
overlying	06-MPB-011	moderate	0	N/A	8.4	714	10714	456	0	0	97	244.6	509.0	3454	147
overlying	06-MPB-012	strong	0	N/A	9.4	213	15957	68	21	0	70	175.1	428.7	1182	159
down ice	06-MPB-036	weak	1	S	9.9	10	5	10	40	0	7	4.2	15.3	168	16
down ice	06-MPB-037	weak	1	S	8.6	7	5	2	58	0	4	7.7	10.2	97	9
down ice	06-MPB-019	weak	2	S	8.8	11	91	13	23	0	35	14.9	23.0	272	14
down ice	06-MPB-023	moderate	2	S	9.6	10	5	17	104	0	4	3.0	12.2	728	98
down ice	06-MPB-035	weak	2	S	8.0	25	100	35	25	0	10	28.9	26.8	338	10
down ice	06-MPB-022	moderate	7	E	8.8	8	3	3	45	0	7	2.9	2.1	115	115
down ice	06-MPB-027	strong	10	S	8.7	57	22	32	92	0	21	29.7	12.0	242	15
down ice	06-MPB-024	strong	20	S	11.3	13	5	18	106	0	3	2.3	1.8	63	11
down ice	06-MPB-013	moderate	25	W	6.8	4	0	6	44	0	9	26.2	59.0	757	14
down ice	06-MPB-025	strong	32	S	10.2	29	6	34	78	0	15	8.2	8.2	190	6
down ice	06-MPB-026	strong	37	S	7.9	25	10	32	127	0	8	5.9	5.8	233	14
down ice	06-MPB-028	strong	55	S	10.6	0	4	11	94	0	3	3.7	11.9	66	20
down ice	06-MPB-029	strong	110	S	8.2	0	4	6	98	0	4	2.6	2.6	54	11
down ice	06-MPB-034	strong	170	S	7.6	0	4	5	132	0	5	4.2	4.2	95	10
down ice	06-MPB-033	strong	190	S	8.6	2	3	16	116	0	3	5.2	2.7	67	11
down ice	06-MPB-032	strong	200	S	9.9	1	0	2	101	0	7	2.3	4.5	53	19
down ice	06-MPB-031	strong	600	S	9.4	21	0	9	53	0	2	2.6	1.9	56	10
down ice	06-MPB-030	weak	1500	SE	8.7	0	0	3	57	0	7	0.8	1.3	32	6
down ice	06-MPB-038	weak	1500	S	8.2	0	0	0	46	0	3	4.5	3.9	69	8
background	06-MPB-008	strong	5000	S	9.6	4	0	2	52	0	2	2.1	1.9	60	38
background	06-MPB-039	weak	5000	SE	6.5	0	0	0	8	3077	5	3.8	6.4	80	21

Figure 8. Colour photographs of indicator minerals: **a)** a small fragment of gossan sample 06-MPB-010 revealing sperrylite grains in a goethite matrix; **b)** sperrylite grain from till sample 06-MPB-011; **c)** chalcopyrite grains from till sample 06-MPB-027; **d)** pyrite grains from till sample 06-MPB-027; **e)** goethite grains from till sample 06-MPB-009; **f)** epidote grains from till sample 06-MPB-011; **g)** axinite grains from till sample 06-MPB-039; and **h)** titanite grains from till sample 06-MPB-011. Photos by Michael J. Bainbridge Photography.

+ chalcopyrite (Fig. 8a). Thus, it is not unexpected that there are abundant sperrylite grains in the local till samples down-ice.

Figure 9 shows the range in the sizes and shapes of sperrylite grains recovered from till sample 06-MPB-026, collected 37 m down-ice (south) of mineralization. Angular fragments of broken grains up to 100 µm are shown in Figure 9a to f and smaller, intact sperrylite crystals are shown in Figure 9g,h. Till sample 06-MPB-033, collected 190 m down-ice of the mineralization, was found to contain 50 µm sperrylite grains, both an intact crystal (Fig. 10a) and an angular fragment (Fig. 10b). Coarse (>100 µm) sperrylite grains were also recovered from local till samples. Samples 06-MPB-011, -012, and -027 contained one to two grains that were 0.25–1.0 mm in diameter (Appendix B, worksheet "MMSIM").

Gold

A threshold of 5 grains/10 kg was established between background and anomalous numbers of gold grains in till samples in the region around Broken Hammer using data from Bajc and Hall (2000). Map 2 in Appendix D shows the distribution of gold grains in Bajc and Hall's regional till samples around the Broken Hammer study site. The three background till samples collected 6000 m up-ice of the Broken Hammer deposit contain between 4 and 28 gold grains/10 kg. Metal-rich till proximal (within 10 m) of the Broken Hammer deposit contains between 2 and 456 gold grains/10 kg (Table 2, Appendix D, Map 3). Between 10 and 50 m down-ice, till contains 10s of grains; between 50 and 250 m down-ice, till contains only a few gold grains. Sample 06-MPB-031, collected 600 m down-ice, contains 9 gold grains. Most gold grains in till samples down-ice of the main chalcopyrite vein vary in size (length dimension reported by ODM) between 10 and 50 µm (Table 3a). Most gold grains recovered from gossan sample 06-MPB-010 have a similar size range (Table 3b). Most till samples contain a mixture of pristine to reshaped gold grains, using the gold grain shape classification scheme of DiLabio (1990). However, samples 06-MPB-11, -12, and -18 contain mostly pristine gold grains, reflecting their short glacial transport distance and proximity (<1 m) to mineralization.

Chalcopyrite

Chalcopyrite (Fig. 8c) is by far the most abundant ore mineral in till overlying and down-ice of the deposit, with up ~16,000 grains/10 kg in metal-rich till (Table 2). Background abundances of chalcopyrite in regional till up-ice, as reported by Bajc and Hall (2000) are zero (Appendix D, Map 4). Overlying mineralization, till contains up to 16,000 chalcopyrite grains. Between 10 and 50 m down-ice, till contains 1s to 100 of grains; between 50 and 250 m down-ice, till contains a few (≤10) visible grains. Sample 06-MPB-031, collected 600 m down-ice, contains 0 chalcopyrite grains.

Pyrite

Pyrite (Fig. 8d) abundance in the 0.25–0.5 mm heavy mineral concentrate of background till samples in this study is 3 to 70 grains/10 kg (Table 2). Pyrite content in till overlying and up to 600 m down-ice of the mineralization varies from 0 to 132 grains (Appendix D, Map 5). In contrast to the 0.25–0.5 mm heavy mineral fraction, the pan concentrate of till sample 06-MPB-011 was found to contain approximately 2000 grains (Appendix B, worksheet "Detailed VG").

Geothite

Goethite (Fig. 8e) is present in trace amounts in all till samples (Appendix B, worksheet "MMSIM"). The actual numbers of grains per sample was not reported by ODM.

Epidote

Thousands of epidote (Fig. 8f) grains are present in each till sample. Epidote is listed as present of as part of the background assemblage of the heavy mineral concentrate of each till sample examined (Appendix B, worksheet "MMSIM"). The exact number of grains in each till sample is listed in Appendix B, worksheet "Epidote estimates". A selection of 30 to 40 epidote grains from nine till samples overlying and at varying distances down-ice of mineralization were analyzed by EMP to confirm their identification and characterize the variation in composition versus proximity to mineralization. EMP data are listed in Appendix C2.

Axinite

Axinite ($Ca_2MgAl_2(BO_3)Si_4O_{12}(OH)$) grains (Fig. 8g) were recovered only from till sample 06-MPB-039 (Table 2), collected 5 km down-ice of the Broken Hammer deposit at the south end of Joe Lake and overlying the Onaping Formation (Fig. 2). A total of 23 axinite grains recovered from the 0.25–0.5 mm heavy mineral fraction of till sample 06-MPB-039 were analyzed by EMP to confirm their identification. EMP data are listed in Appendix C3 and C4.

Titanite

Titanite grains were visually identified in selected till heavy mineral concentrates by their brown colour (Fig. 8h) and selectively picked from eight till samples (Appendix B, worksheet "Additional Picking") overlying and at varying distances down-ice of mineralization to examine their compositional range. The total number of grains in each till sample was not determined. Selected grains were analyzed by EMP to confirm their

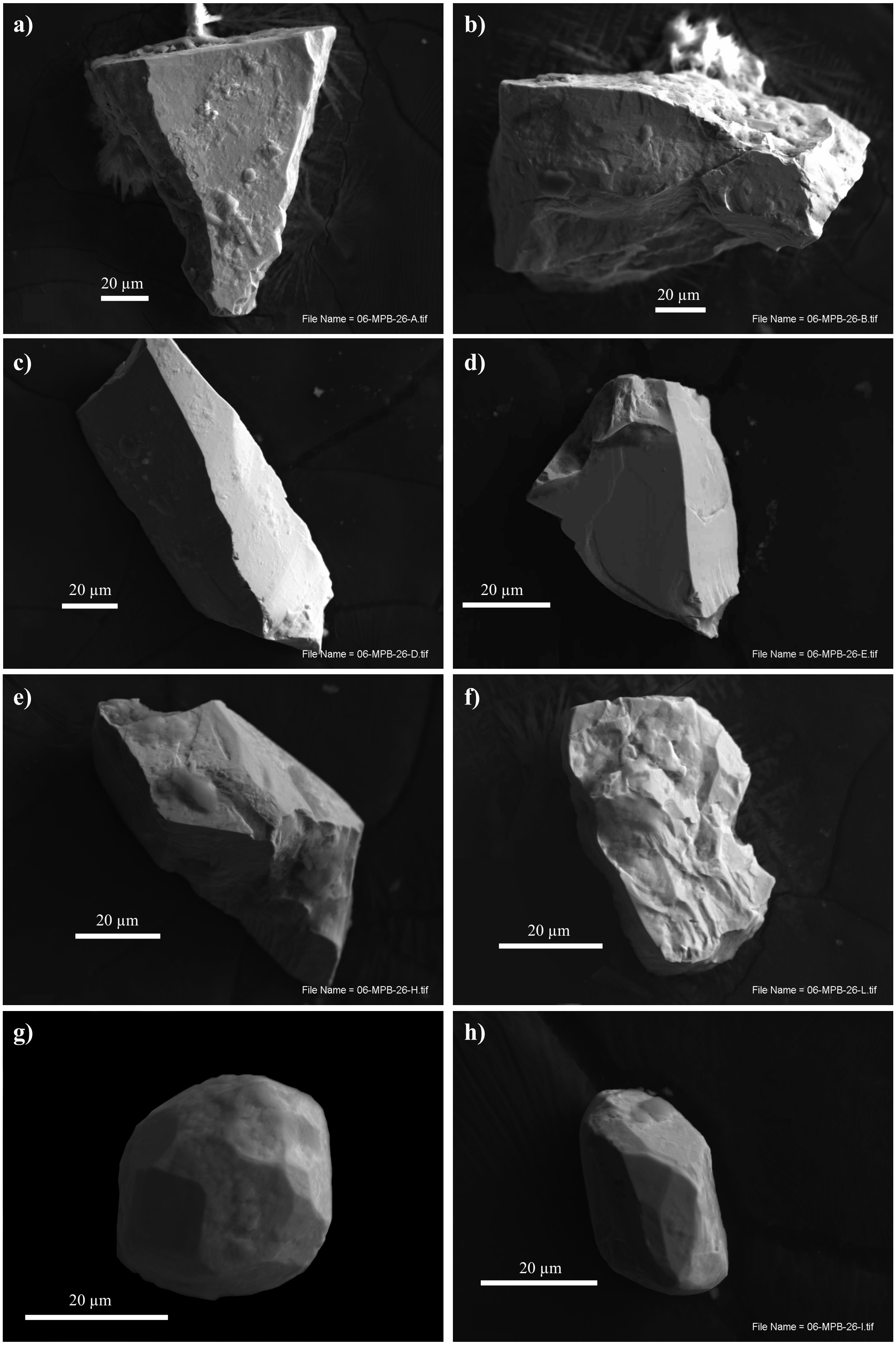


Figure 9. Scanning electron microscope electron backscatter images of sperrylite grains recovered from till sample 06-MPB-026, collected 50 m down-ice (south) of mineralization, shows the variable size and shape of the grains: **a to f)** angular fragments of broken grains up to 100 µm in diameter, **g and h**) smaller, intact sperrylite crystals.

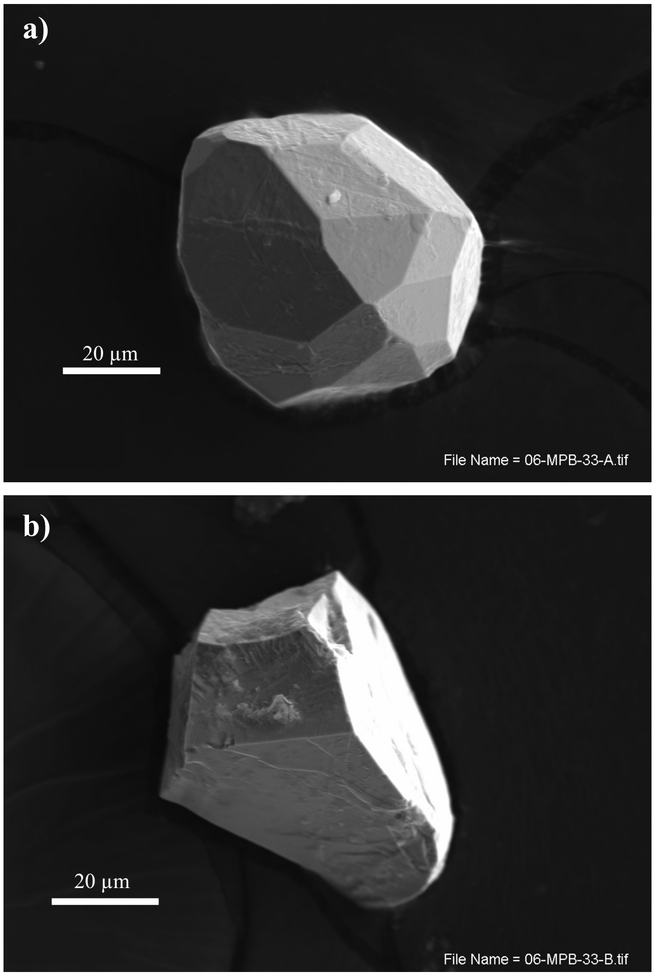


Figure 10. Scanning electron microscope electron backscatter images of sperrylite grains recovered from till sample 06-MPB-033, which was collected 170 m down-ice of the mineralization: **a)** intact crystal, and **b)** angular fragment.

Table 3. Number and size of the largest dimension of the gold grains in **(a)** till samples near the Broken Hammer deposit, and **(b)** gossan sample 06-MPB-010.

a) Gold grains in till samples

10	15	25	50	75	100	125	150	175	200	µm	
41	0	0	0	0	0	0	0	0	0	**10**	silt
0	22	0	0	0	0	0	0	0	0	**15**	
0	130	180	0	0	0	0	0	0	0	**25**	
0	0	145	53	0	0	0	0	0	0	**50**	
0	0	6	58	10	0	0	0	0	0	**75**	very fine sand
	0	0	17	11	2	0	0	0	0	**100**	
		0	3	4	3	0	0	0	0	**125**	
			0	2	4	0	1	0	0	**150**	fine sand
				0	0	0	0	0	0	**175**	
					1	0	0	0	0	**200**	
						0	0	0	0	**225**	
						1	0	0	1	**250**	

b) Gold grains in gossan sample 06-MPB-010

10	15	25	50	75	100	125	150	µm	
40	0	0	0	0	0	0	0	**10**	silt
	0	0	0	0	0	0	0	**15**	
	79	87	0	0	0	0	0	**25**	
		53	21	0	0	0	0	**50**	
		8	4	2	0	0	0	**75**	very fine sand
			1	2	0	0	0	**100**	
				1	0	0	0	**125**	
				1	0	0	0	**150**	← fine sand

identification and to characterize the variation in composition versus proximity to mineralization. EMP data are listed in Appendix C5.

Apatite

Apatite grains were selectively picked from the >3.2 SG heavy mineral concentrate of eight till samples (Appendix B, worksheet "Additional Picking"), overlying and at varying distances down-ice of mineralization, to examine their compositional range. Selected grains were analyzed by EMP to confirm their identification and to characterize the variation in composition versus proximity to mineralization. Apatite EMP data are reported in Appendix C6.

DISCUSSION

The main metallic minerals recovered from till samples in this study are chalcopyrite, pyrite, sperrylite, and gold. Between 50 m and 250 m down-ice, till contains a few visible sperrylite grains and ≤16 gold grains. Beyond 250 m down-ice, the spacing of the till samples was not sufficient to determine the distance down-ice that mineralogical signatures from the Broken Hammer deposit may or may not be detected. However, one till sample (06-MPB-031) collected 600 m down-ice did contain a 21 sperrylite grains (Table 2).

The well preserved sperrylite in the till samples and one gossan samples is an indication that sperrylite is resistant to surficial weathering and is a useful indicator mineral for detecting the presence of PGM mineralization in the Sudbury region. Other PGM present in the gossan (Fig. 6) were not recovered from the pan concentrate of till samples. Pyrite, pentlandite, and pyrrhotite, also present in the deposit, were not recovered from the till samples. Their absence may be due to the moderate to high degree of oxidation that has affected the till combined with their instability in the surface weathering environment, relative to chalcopyrite and sperrylite (Averill, 2011).

Axinite is a hydrothermal alteration mineral. It was only recovered from one till sample (06-MPB-039) that overlies the Onaping Formation (Fig. 2), which is host to numerous hydrothermal Zn-Cu-Pb occurrences and deposits (Ames et al., 2006). In addition to containing axinite, this till sample contains the highest Mo, Zn, Pb, and Cd contents in this study. The presence of axinite combined with the elevated metal values may reflect the presence of volcanogenic massive sulphide mineralization nearby. No systematic patterns are apparent for the distribution of epidote, apatite, or titanite with respect to the location of mineralization, thus they are not considered to be useful indicator minerals for this deposit.

CONCLUSIONS

This open file describes the indicator mineral data for 34 till samples from the vicinity of the Broken Hammer Cu-Ni-PGE-Au deposit. Ore minerals recovered from till include chalcopyrite, pyrite, sperrylite, and gold. These heavy minerals (Table 1) are visually distinct and can be easily recovered by common surficial sample processing methods (cf., McClenaghan, 2011) used to recover indicator minerals. Sperrylite grains as large as 1.0 mm were recovered from the till. This is not unexpected, as the deposit is known to contain large, world-class sperrylite crystals. Metal-rich till at Broken Hammer contains up to 714 sperrylite grains, 456 gold grains, and ~11,000 chalcopyrite grains/10 kg. This study is the first to report such high abundances of sperrylite grains in till.

Historically, till sampling has not been used for Cu-Ni-PGE exploration in the Sudbury region. This study demonstrates that indicator mineral methods can be a useful exploration technique for detecting footwall-hosted Cu-Ni-PGE style of mineralization. Till sampling 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 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. 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 in the till indicates that oxidized till is also worthwhile sampling if it is the only medium available.

ACKNOWLEDGEMENTS

Funding for this study was provided under the Geological Survey of Canada's Targeted Geoscience Initiative 3 (TGI-3) (2005-2010). G. Budulan (University of Ottawa summer student) provided able field assistance in 2006. Wallbridge Mining Company Ltd. and, in particular, B. Jago, M. Croteau, and P. Anderson, are thanked for providing access, field support, confidential geological information and samples, and field personnel to assist with the sampling. M. Stewart of Vale is thanked for access to information and samples for the Wisner west area. C. Farrow, FNX Mining Company Inc., is thanked for providing geological discussions and guidance in selecting study sites. W. Spirito, GSC, is thanked for reviewing the manuscript. Page layout was completed by E. Ambrose.

REFERENCES

Ames, D.E. and Farrow, C.E.G., 2007. Metallogeny of the Sudbury mining camp, Ontario, *In:* Mineral Deposits of Canada: A Synthesis of Major Deposit-Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods, (ed.) W.D. Goodfellow; Geological Association of Canada, Mineral Deposits Division, Special Publication No. 5., p. 329–350.

Ames, D.E. and Kjarsgaard, I.M., 2013. Sulphide and alteration mineral chemistry of low- and high- sulphide Cu-PGE-Ni deposits in the footwall environment, Sudbury, Canada; Geological Survey of Canada, Open File 7331.

Ames, D.E., Davidson, A., Buckle, J.L., and Card, K.D., 2005. Geology, Sudbury bedrock compilation, Ontario; Geological Survey of Canada, Open File 4570.

Ames, D.E., Jonasson, I.R., Gibson, H.L., and Pope, K.O., 2006. Impact-generated hydrothermal system - Constraints from the large Paleoproterozoic Sudbury crater, Canada, *In:* Biological Processes associated with Impact Events, Impact Studies; (eds) C. Cockell, I. Gilmour, and C. Koeberl; Springer-Verlag, Berlin-Heidelberg, p. 55–100.

Ames, D.E., McClenaghan, M.B., and Averill, S., 2007. Footwall-hosted Cu-PGE (Au, Ag), Sudbury Canada: towards a new exploration vector, in Exploration 07, Exploration in the New Millennium, Proceedings of the Fifth Decennial International Conference on Mineral Exploration, p. 1013–1017.

Ames, D.E., Kjarsgaard, I.M., and McClenaghan, M.B., 2013a. Target characterization of footwall Cu-(Ni)-PGE deposits, Sudbury; Geological Survey of Canada, Open File 7329.

Ames, D.E., Hanley, J., Tuba G., and Jackson, S., 2013b. High-grade sperrylite zone reveals primitive source in the Sudbury impact structure; Mineralogical Magazine, v. 77, p. 587.

Armstrong, J.T., 1988. Quantitative analysis of silicates and oxide minerals: comparison of Monte-Carlo, ZAF and Phi-Rho-Z procedures, *In:* Microbeam Analysis, (ed.) D.E. Newbury; San Francisco Press, San Francisco, California, p. 239–246.

Averill, S.A., 2011. Viable indicator minerals in surficial sediments for two major base metal deposit types: Ni-Cu-PGE and porphyry Cu; Geochemistry: Exploration, Environment, Analysis, v. 11, p. 279–291.

Bajc, A.F. 1997a. Quaternary geology, North and East ranges, Sudbury Basin: east-central part; Ontario Geological Survey, Map 2521, scale 1:20,000.

Bajc, A.F., 1997b. Quaternary Geology, North and East Ranges, Sudbury Basin, District of Sudbury: Western Part; Ontario Geological Survey, Map 2519, scale 1:20,000.

Bajc, A.F., 1997c. Quaternary Geology, North and East Ranges, Sudbury Basin, District of Sudbury: West-central Part; Ontario Geological Survey, Map 2520, scale 1:20,000.

Bajc, A.F. and Hall, G.E.M., 2000. Geochemical response of surficial media, north and east ranges, Sudbury Basin; Ontario Geological Survey, Open File Report 6033, 265 p.

Barnett, P.J. and Bajc, A.F., 2002. Quaternary geology, Chapter 3 *In:* Physical Environment-Sudbury; Ontario Geological Survey, Special Volume 6, p. 57–78.

Boissoneau, A.N., 1968. Glacial history of northeastern Ontario II. The Timiskaming-Algoma area; Canadian Journal of Earth Sciences, v. 5, p. 97–109.

Card, K.D., 1994. Geology of the Levack gneiss complex, the northern footwall of the Sudbury structure, Ontario, *In:* Current Research 1994-C; Geological Survey of Canada, p. 269–278.

Coats, C. and Snajdr, P., 1984 Ore deposits of the North Range, Onaping-Levack Area, Sudbury, *In:* The Geology and Ore Deposits of the Sudbury Structure, (eds) E.G. Pye, A.J. Naldrett, and P.E. Giblin; Ontario Geological Survey, Special Volume 1, p. 327–345.

DiLabio, R.N.W., 1990. Classification and interpretation of the shapes and surface textures of gold grains from till on the Canadian Shield, *In:* Current Research, Part C; Geological Survey of Canada, Paper 90-1C, p. 323–329.

Doran, R., Churchill, B.C., Cox, J.J., and McBride, T., 2012. Prefeasibility report on the Broken Hammer project, Sudbury, Ontario, Canada; prepared for Wallbridge Mining Company Limited, Report for NI 43-101.

Farrow, C.E.G., Watkinson, D.H., and Jones, P.C., 1994. Fluid inclusions in sulfides from North and South Range Cu-Ni-PGE deposits, Sudbury Structure, Ontario; Economic Geology, v. 89, p. 647–655.

Farrow, C.E.G., Everest, J.O., King, D.M., and Jolette, C., 2005. Sudbury Cu-(Ni)- PGE systems: refining the classification using McCreedy West Mine and Podolsky Project case studies; Mineralogical Association of Canada, Short Course 35, p. 163–180.

Hanley, J.J., Mungall, J.E., Pettke, T., and Spooner, E.T.C., 2005. Ore metal redistribution by hydrocarbon-brine and hydrocarbon-halide melt mixtures, North Range footwall of the Sudbury Igneous Complex, Ontario, Canada; Mineralium Deposita, v. 40, p. 237–256.

Hanley, J., Ames, D, Barnes, J., Sharp, Z., and Pettke, T., 2006. Stable isotope evidence for multiple sources of Cl in ore fluids at the Sudbury Igneous Complex, Ontario, Canada; Geological association of Canada – Mineral Deposits Division, The Gangue, p. 4–10.

Kjarsgaard, I.M. and Ames, D.E., 2010. Ore mineralogy of Cu-Ni-PGE deposits in the North Range footwall environment, Sudbury, Canada, *In:* Abstracts, 11th International Platinum Symposium, 21-24 June 2010, Sudbury, Ontario, Canada, (eds) G.H. Brown, P.J. Jugo, C.M. Lesher, J.E. Mungall; Ontario Geological Survey, Miscellaneous Data Release - Data 269.

Lydon, J.W., 2007. An overview of the economic and geological contexts of Canada's major mineral deposit type, *In:* Mineral Deposits of Canada: a Synthesis of Major Deposit-Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods; (ed.) W.D. Goodfellow; Geological Association of Canada, Mineral Deposits Division, Special Publication No. 5, p. 3–48.

McClenaghan, M.B., 2011. Overview of common processing methods for recovery of indicator minerals from sediment and bedrock in mineral exploration; Geochemistry: Exploration, Environment, Analysis, v. 11, p. 265–278.

McClenaghan, M.B. and Ames, D.E., 2013. Indicator mineral abundance data for bedrock and till from the footwall-type Cu-Ni-PGE Broken Hammer occurrence, Sudbury, Ontario; Geological Survey of Canada, Open File 7388.

McClenaghan, M.B., Ames, D.E., Buckle, J.L., and Bajc, A.F., 2014. Till geochemical signatures of the Broken Hammer Cu-(Ni)-PGE occurrence, North Range, Sudbury Structure, Ontario; Geological Survey of Canada, Open File 7602.

McClenaghan, M.B., Kjarsgaard, I.M., and Ames, D.E., in press. Indicator mineral data for bedrock samples from the Broken Hammer Cu-Ni-PGE-Au deposit, north range, Sudbury structure, Ontario; Geological Survey of Canada, Open File 8369.

Mealin, C.A., 2005. Characterization of the Ni-Cu-PGE Mineralization observed at the Broken Hammer occurrence, Wisner Property, Sudbury; B.Sc. thesis, University of Waterloo, 185 p.

O'Callaghan, J.W.O., Osinski, G.R., Lightfoot, P.C., and Linnen, R.L., 2016a. Reconstructing the geochemical signature of Sudbury Breccia, Ontario, Canada: implications for its formation and trace metal content; Economic Geology, v. 111, p. 1705–1729.

O'Callaghan, J.W.O., Osinski, G.R., Lightfoot, P.C., and Linnen, R.L., 2016b. Reconstructing the geochemical signature of Sudbury Breccia, Ontario, Canada: implications for exploration models; Applied Earth Science, Transactions of the Institutions of Mining and Metallurgy, Section B, v. 125, p. 92–93.

Péntek, A., Molnar, F., and Watkinson, D.H., 2006. Multiple hydrothermal processes at the footwall-type Cu-Ni-PGE mineralization of the Broken Hammer area, Wisner Property, Sudbury Igneous Complex, Canada; Society of Economic Geologists, Abstracts, 14–16 May, 2006, Keystone Colorado.

Péntek, A., Molnár, F., Watkinson, D.H., and Jones, P.C., 2008. Footwall-type Cu-Ni-PGE mineralization in the Broken Hammer area, Wisner Township, North Range, Sudbury Structure; Economic Geology, v. 103, p. 1005–1028.

Peterson, D.M., Kutluoglu, R.A., and Little, T.L., 2004. Bedrock geology map of the Broken Hammer and Bog Boy vein trench area; Report prepared for Wallbridge Mining Company Ltd., unpublished map.

Speers, E., 1957. The age relation and origin of common Sudbury Breccia; Journal of Geology, v. 65, p. 497–514.

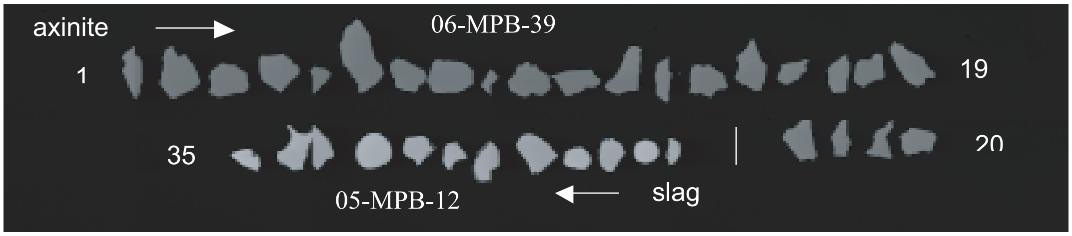
Wallbridge Mining Company Ltd., 2018. Website http://www.wallbridgemining.com/s/broken-hammer.asp Accessed March 18, 2018.

Watkinson, D.H., Jones, P., and Wallbridge staff, 2005. Palladium minerals and hydrous silicate assemblages from the Broken Hammer Zone, Wisner Property of the north range footwall, Sudbury Igneous Complex; Geological Association of Canada, Halifax 2005 Abstracts, p. 204–205.

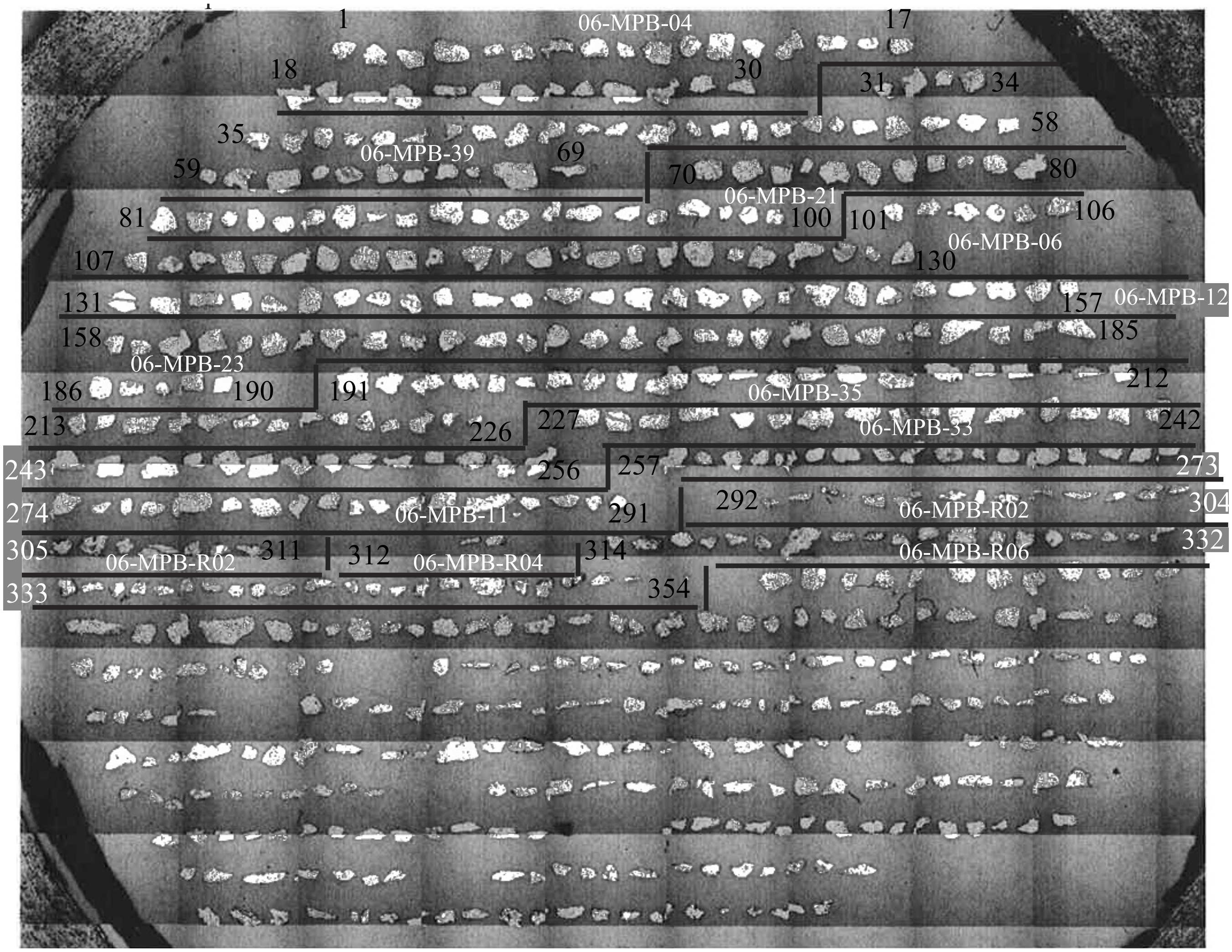
Wilson, B., 2012. New sperrylites from Canada; Minerals, v. 4, p. 1–8

APPENDICES

Appendix C1. Grain mount maps for electron microprobe analysis.

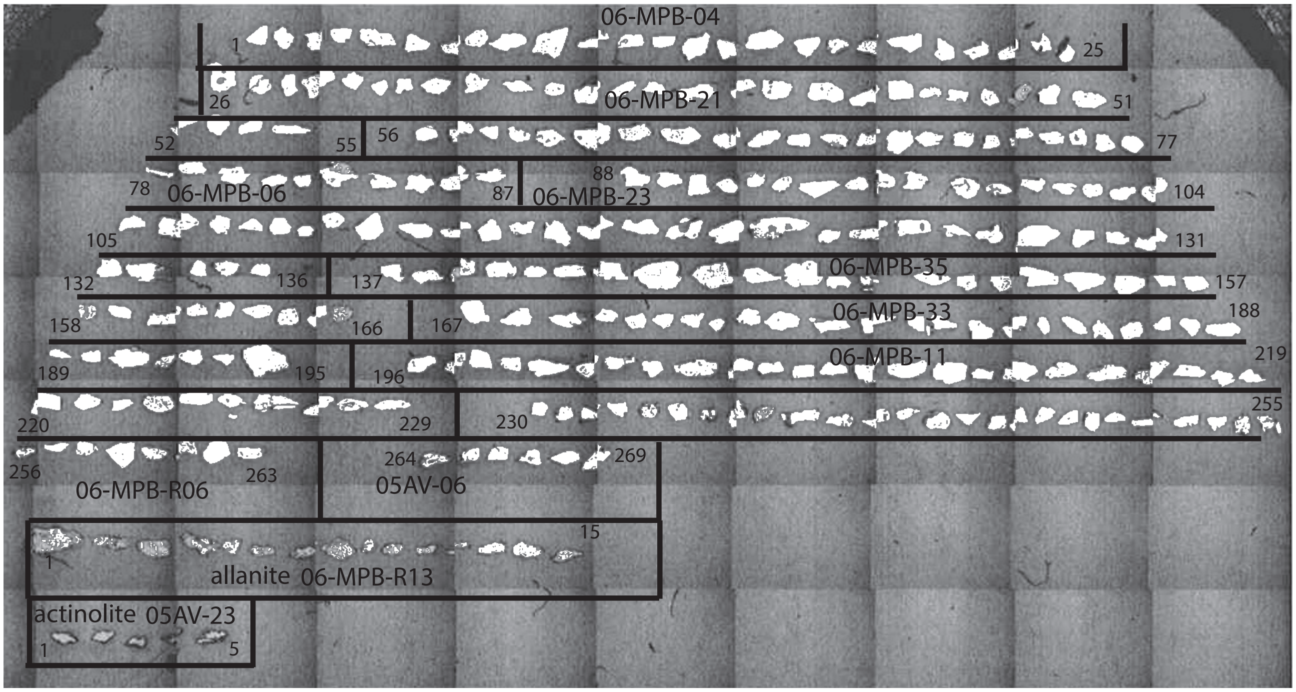


Grain mount map 06-0537-P07, Axinite grains in the 0.25–0.50 mm fraction of sample 06-MPB-39.

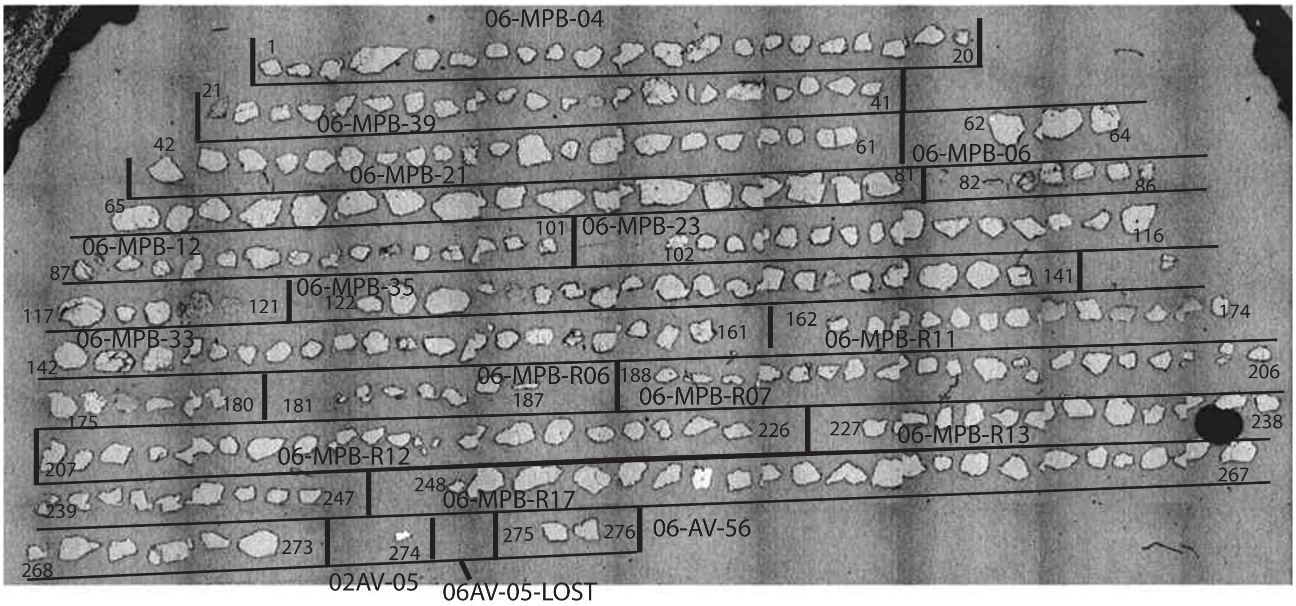


Grain mount map 22713, 0.25–0.50 mm fraction of till samples 06-MPB-04, -06, -11, -12, -20, -23, -33, -35, and -39.

Appendix C1 continued.

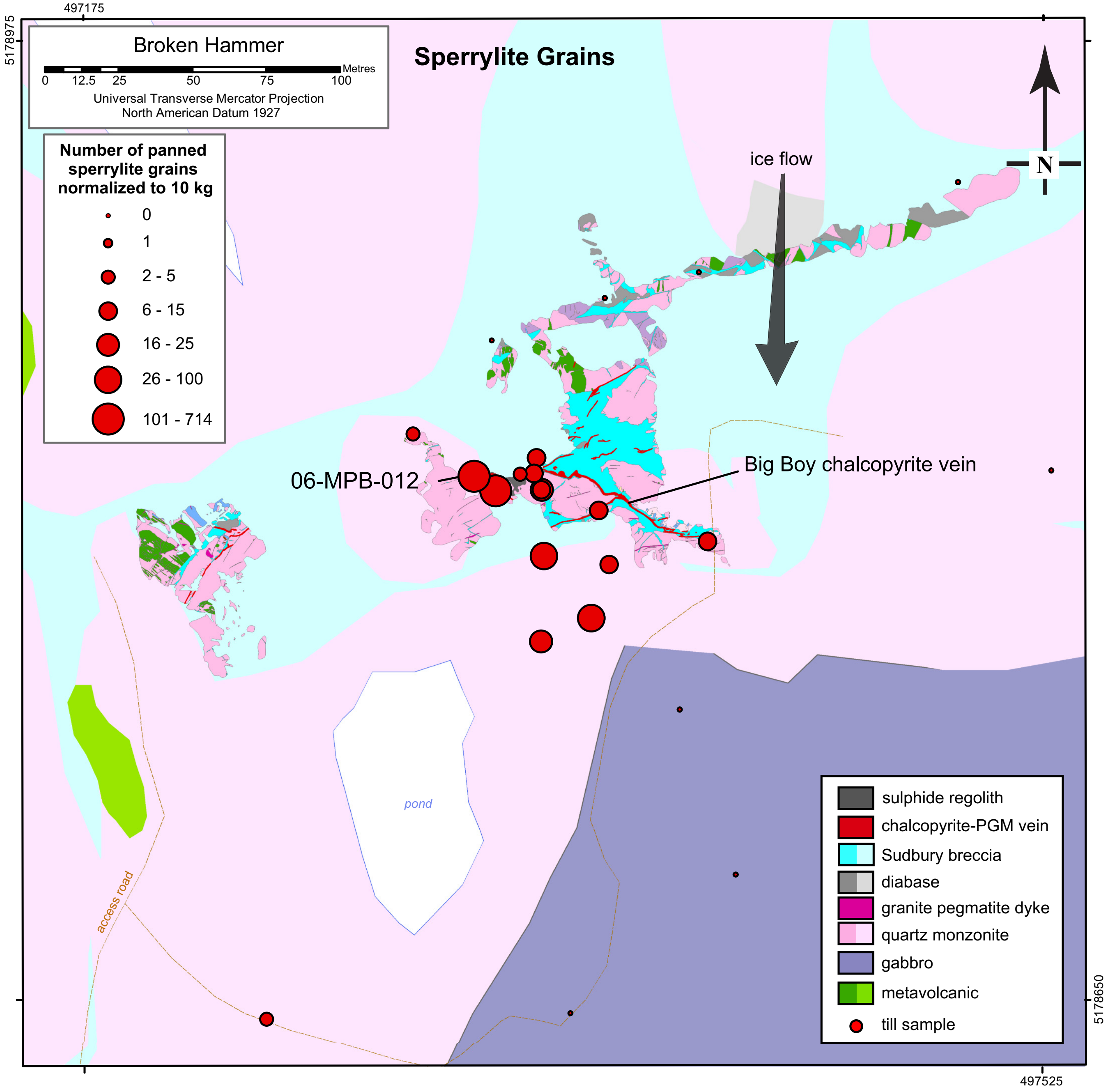


Grain mount map 22714, 0.25–0.50 mm fraction of till samples 06-MPB-04, -06, -11, -21, -23, -33, -35, and -39.



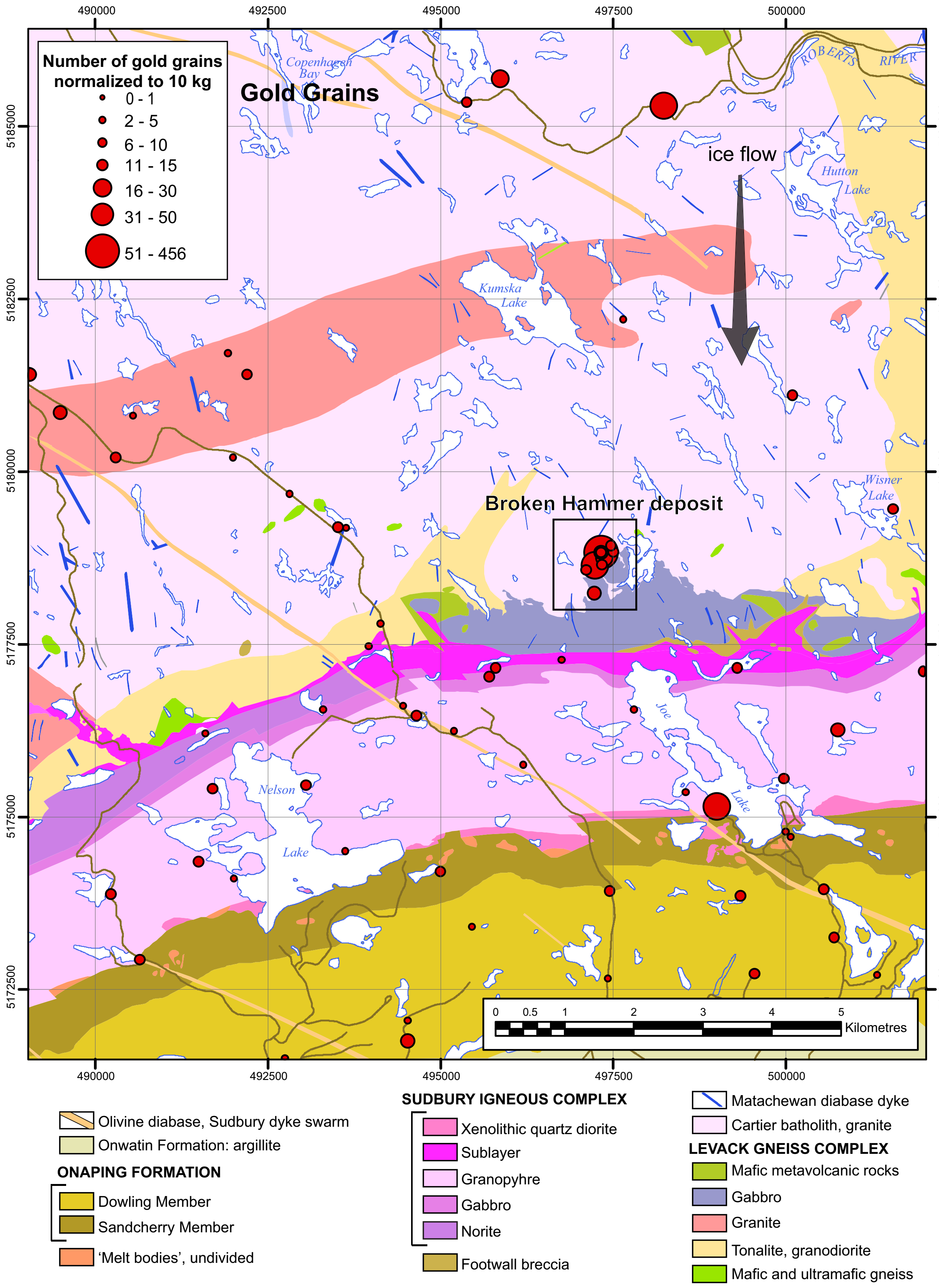
Grain mount map 22716, Apatite grains in the 0.25–0.50 mm fraction of till samples 06-MPB-04, -06, -12, -21, -23, -33, and -35.

Appendix D. Proportional dot maps of indicator mineral abundance.



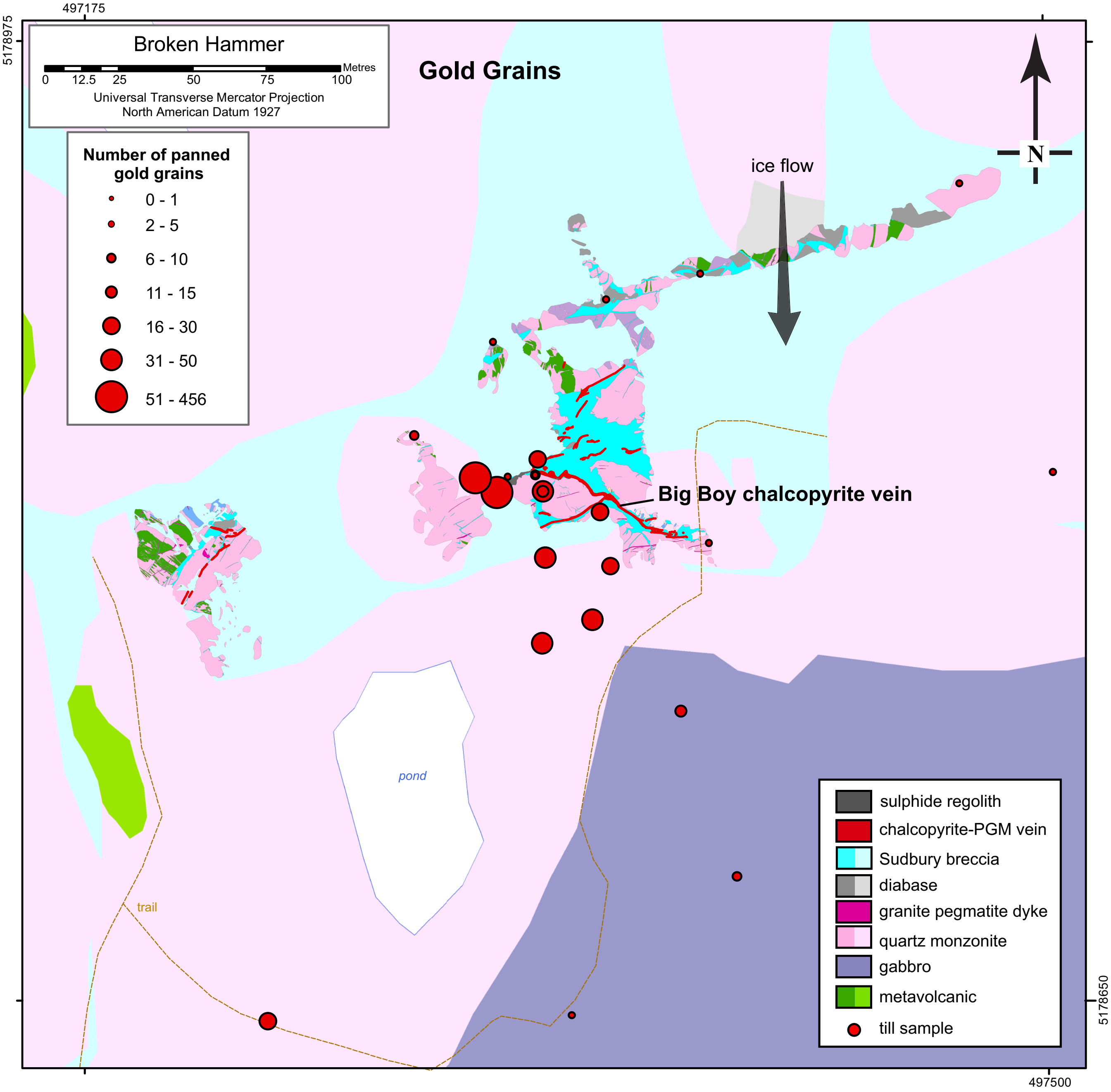
Appendix D, Map 1. Proportional dot map of sperrylite grains in pan concentrates of till samples collected proximal to the Broken Hammer deposit (normalized to a 10 kg sample weight) (detailed bedrock geology from Peterson et al. 2004; regional bedrock geology from Ames et al., 2005) (datum NAD27).

Appendix D continued.



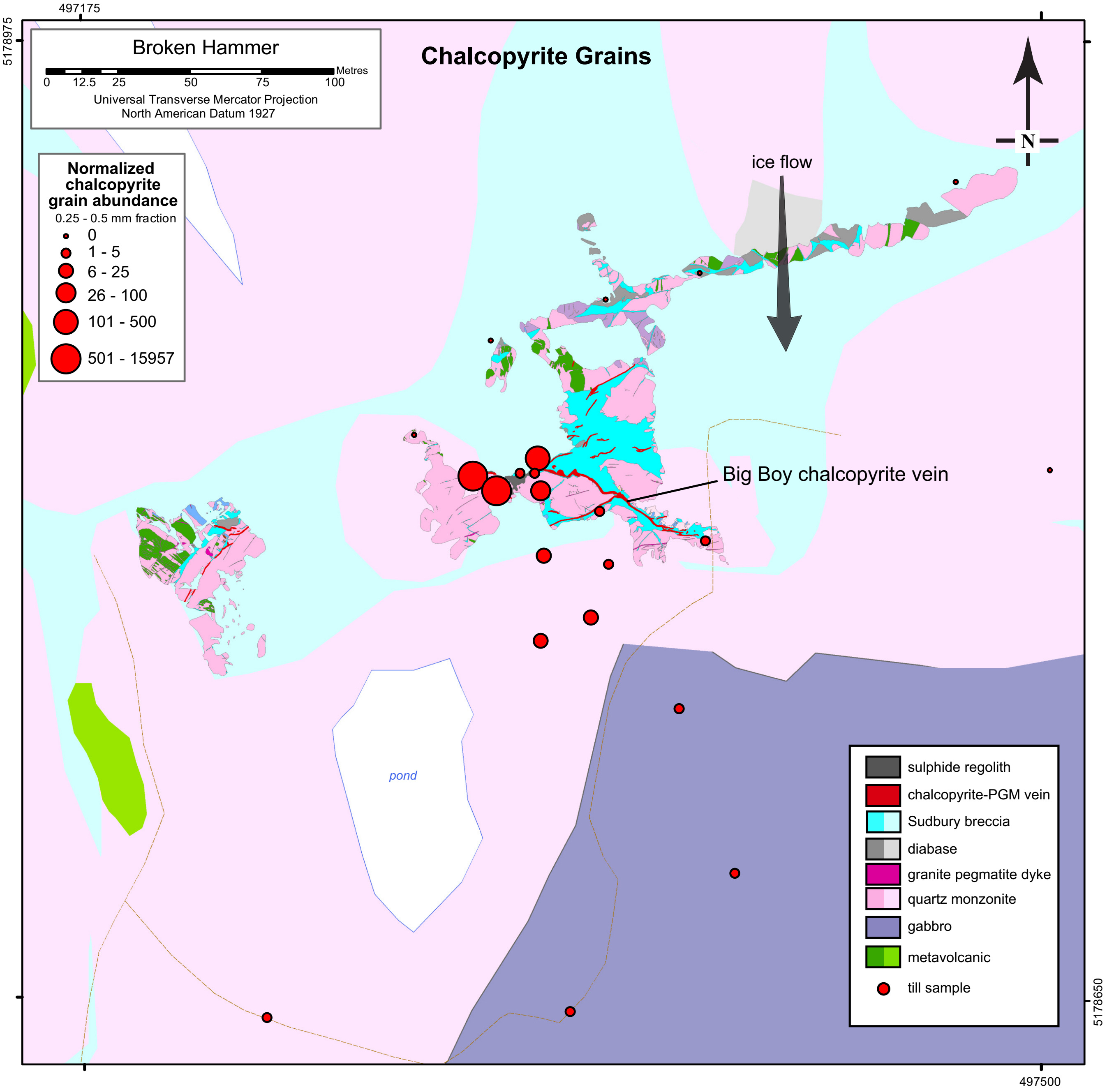
Appendix D, Map 2. Proportional dot map of the number of gold grains in the pan concentrates of till samples collected by the GSC around the Broken Hammer deposit (normalized to a 10 kg sample weight) (regional bedrock geology from Ames et al., 2005).

Appendix D continued.



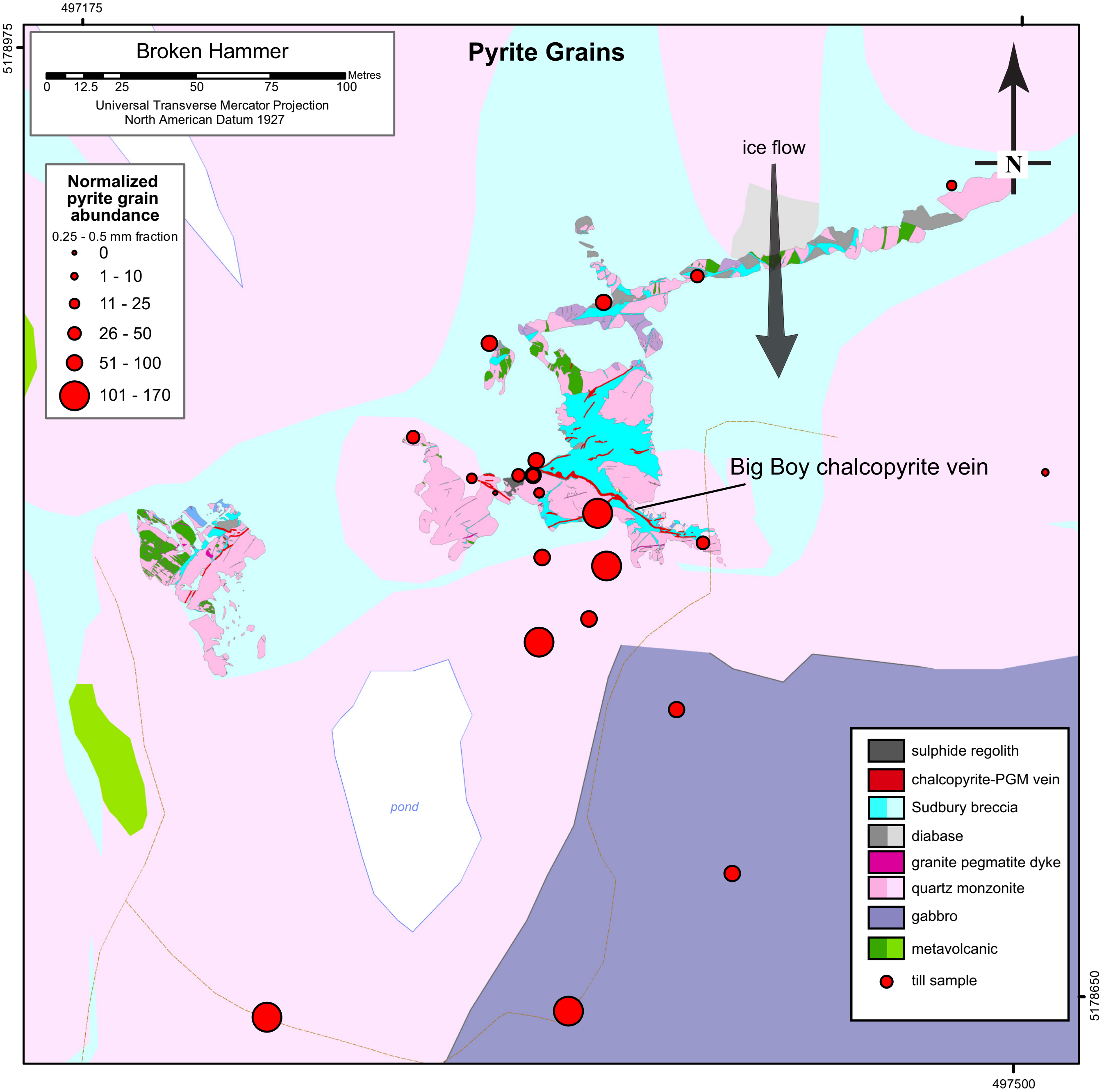
Appendix D, Map 3. Proportional dot map of gold grains in pan concentrates of till samples collected proximal to the Broken Hammer deposit (normalized to a 10 kg sample weight) (detailed bedrock geology from Peterson et al. 2004; regional bedrock geology from Ames et al., 2005) (datum NAD27).

Appendix D continued.



Appendix D, Map 4. Proportional dot map of chalcopyrite grains in the 0.25–0.5 mm fraction of heavy mineral concentrates of till samples collected proximal to the Broken Hammer deposit (normalized to a 10 kg sample weight) (detailed bedrock geology from Peterson et al. 2004; regional bedrock geology from Ames et al., 2005) (datum NAD27).

Appendix D continued.



Appendix D, Map 5. Proportional dot map of pyrite grains in the 0.25–0.5 mm fraction of heavy mineral concentrates of till samples collected proximal to the Broken Hammer deposit (normalized to a 10 kg sample weight) (detailed bedrock geology from Peterson et al. 2004; regional bedrock geology from Ames et al., 2005) (datum NAD27).