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Publications in this series have not been edited; they are released as submitted by the author.

Contribution to the Geological Survey of Canada's Targeted Geoscience Initiative 3 (TGI-3) Program (2005-2010)

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TILL GEOCHEMICAL SIGNATURES OF THE BROKEN HAMMER CU-(NI)-PGE OCCURRENCE, NORTH RANGE, SUDBURY SRUCTURE, ONTARIO

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ABSTRACT

The Geological Survey of Canada conducted detailed till sampling around the Broken Hammer Cu-(Ni)-PGE occurrence in the North Range of the Sudbury Structure, northeastern Ontario, to document the indicator mineral and multi-element geochemical signature in the till. The Broken Hammer occurrence consists of a shallow surface zone of vein and vein stockwork-hosted Cu-PGE mineralization within Sudbury breccia developed in the NeoArchean quartz-monzonite Levack Gneiss Complex. It consists of a main 2 to 120 cm wide chalcopyrite vein dominated by chalcopyrite-magnetite-millerite with numerous trace and rare precious metal minerals, including tellurides, bismuthides, selenides, and stannides. The Laurentide Ice Sheet flowed southward across the Broken Hammer region depositing a sandy till. The main indicator minerals in till overlying and just down-ice of the occurrence include sperrylite, chalcopyrite, and gold. The <0.063 mm size fraction of till overlying and just down-ice of the occurrence displays a strong geochemical signature of the mineralization, most notably for Pd, Pt, Au, and Cu, as well as Ni, Ag, Cd, Sb, Bi, Se, Te, Tl, and Sn.

INTRODUCTION

The use of till geochemistry for magmatic Ni-Cu-PGE exploration in glaciated terrain has been described by only a few researchers (Coker et al., 1990, 1991; Tiainen et al., 1991; Cook and Fletcher, 1992; Barnett, 2007; McClenaghan et al., 2011). Even fewer studies report the indicator mineral signatures of this deposit type in till (Bajc, 2000; Bajc and Hall, 2000; Searcy, 2001). 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 till samples from around the Broken Hammer Cu-(Ni)-PGE occurrence on the North Range of the Sudbury Structure, northeastern Ontario (Fig. 1).

The Broken Hammer occurrence was chosen as a Ni-Cu-PGE indicator mineral test site because its mineralized zone is known to contain visible sperrylite ($PtAs_2$), the local area is till covered, the site is easily accessible, and it is located north of the Sudbury Structure and hence up-ice of the major Ni-Cu-PGE deposits, mines, and smelters within the Sudbury region. This report establishes the background concentrations of trace elements in the <0.063 mm size fraction of till in the vicinity of the Broken Hammer occurrence, and documents the multi-element geochemical signature related to the occurrence. Indicator mineral results for these till samples have been reported in GSC Open File 7388 (McClenaghan and Ames, 2013) and detailed interpretation of these results will be reported in a subsequent open file.

LOCATION

The Broken Hammer occurrence is located in Wisner Township, northern Ontario, in the North Range of the Sudbury Structure (latitude 46º45’46” and longitude -82º57’55”) (Fig. 1). The occurrence is 25 km north of the city of Sudbury and is 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 Paleoproterozoic Sudbury world-class nickel mining district is centred on 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. 1). An enormous amount of base and precious metals with over 1.7 billion tonnes of Ni, Cu, Co, Pt, Pd, Au, and Ag ore (Lydon, 2007) has been exploited in this exceptional mining district, and it remains a vital exploration target today. The district’s 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), 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 NeoArchean 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). All of these rocks were strongly affected by the shock and thermal effects of the Sudbury impact at 1850 Ma.

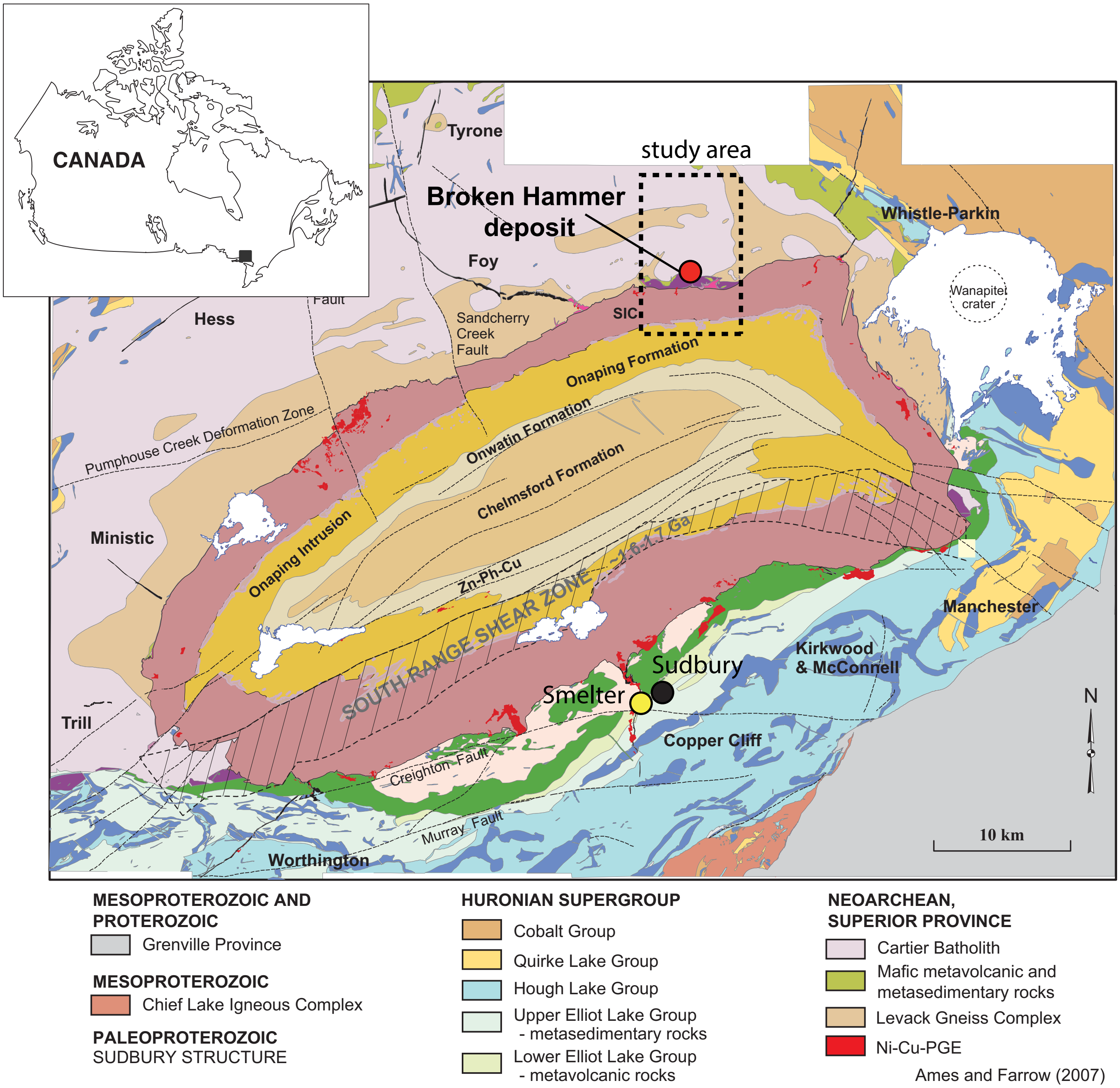


Figure 1. Regional geology map showing the location of the study area, north side of the Sudbury Structure, northeastern Ontario (modified from Ames and Farrow, 2007).

The shocked and brecciated basement rocks (Sudbury breccia unit) and melt rocks (Sudbury Igneous Complex (SIC)) control, 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 mafic SIC, along 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 matrix, which form randomly oriented stringers and large zones or "belts" of breccia up to 200 km from the base of the SIC (Speers, 1957). 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

Though some of the Ni-Cu-PGE mines in the Sudbury region have operated for over a century, new ore deposits and improved ore types, discovered as recently as 2004, have recently come into production or are in the pre-development stage (i.e. advanced prospects). Sudbury Ni-Cu contact-type deposits are

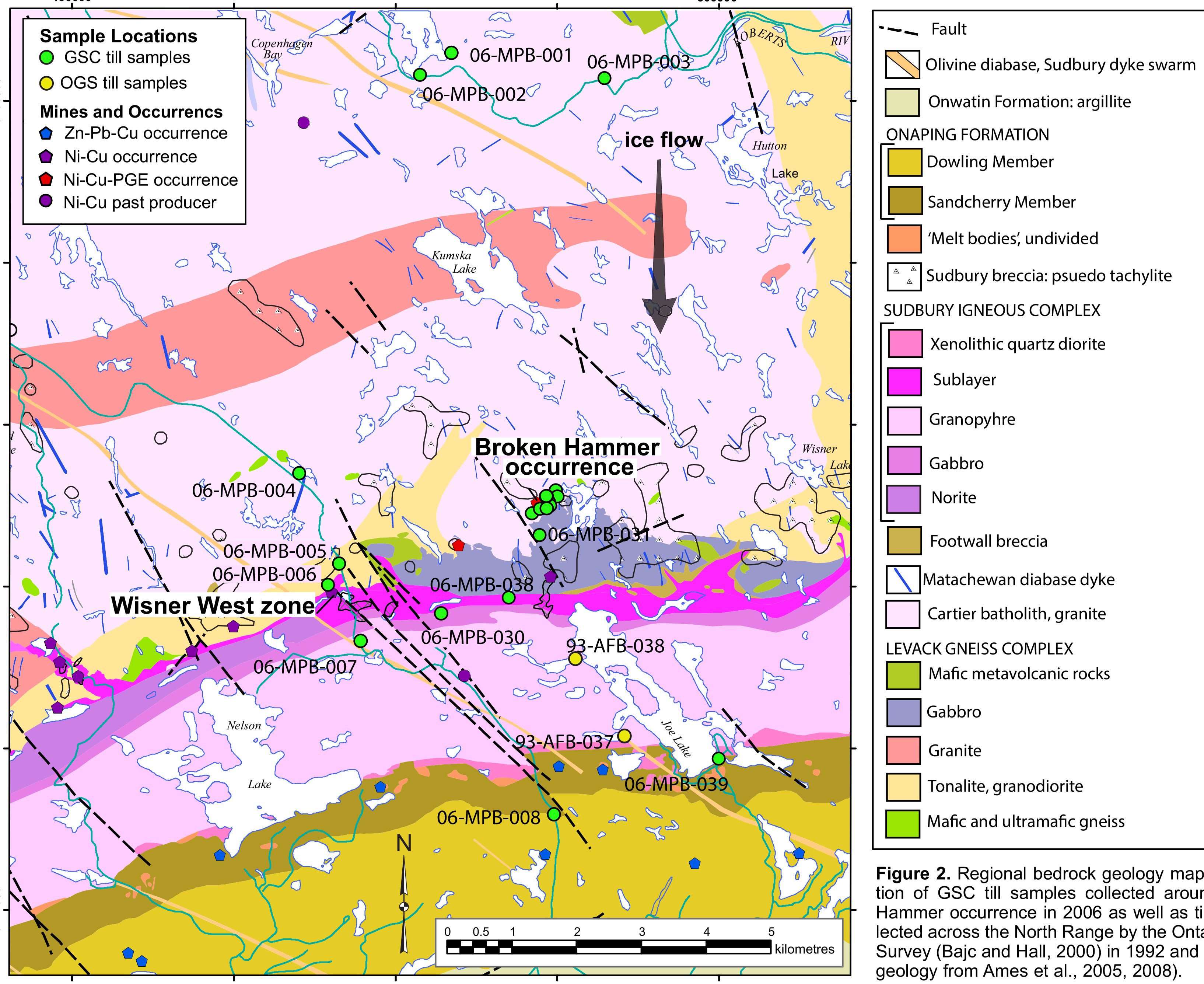


Figure 2. Regional bedrock geology map with the location of GSC till samples collected around the Broken Hammer occurrence in 2006 as well as till samples collected across the North Range by the Ontario Geological Survey (Bajc and Hall, 2000) in 1992 and 1993 (bedrock geology from Ames et al., 2005, 2008).

widely accepted to be of magmatic origin, having formed during differentiation of the Sudbury Igneous Complex (SIC) followed by sulphide segregation and subsequent collection in topographic lows or "embayments" at the base of the SIC. However, the origin of the Cu-Ni-PGE systems remains controversial, with 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 on determining the characteristics, origin, mode of transport, and timing of the low-sulphide PGE-rich mineralization relative to the high-sulfide, largely magmatic veins (Gibson, 2012; White, 2012; Ames and Kjarsgaard, 2013; MacMillan, 2014; Tuba et al., 2014). Later hydrothermal mobilization resulted in redistribution of base and precious metals, modification of the ore composition, and the formation of Cl-rich alteration haloes. Fluid inclusion stable isotope evidence suggests ore metal transport and redistribution involved mixing between regional groundwaters and a metal-rich ore fluid with a magmatic component. This formed 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, with the exception of earlier discoveries of the McCreedy deposits and the Strathcona Deep Copper zone (Coats and Snajdr, 1984) in the Onaping-Levack area. During the last decade, high metal prices triggered an exploration surge for footwall deposits, due to their high copper, precious metal, and PGM content. This exploration surge resulted in the discovery of numerous PGE-rich mineralized zones, such as the Denison 109 footwall zone and Levack North 148 zone (Gibson, 2010), Capre 3000 zone (Stewart and Lightfoot, 2010), Amy zone (Tuba et al., 2014), and the hybrid Broken Hammer zone (Péntek et al., 2008). Footwall Cu-Ni-PGE deposits studied by the GSC include Creighton 403, Creighton Deeps, Barnett, McCreedy East 153 zone, Victor deep, and the recently discovered (2003–2005) Levack Footwall, McCreedy West PM zone, Segway, and Broken Hammer Cu-PGE deposits, advanced prospects, and occurrences (Ames et al., 2007). Sharp-walled deposits are more common. Presently, the only low-sulfide PGE deposit to be mined is the McCreedy West PM zone (Farrow et al., 2005).

Wisner Township bedrock geology and exploration history

The Broken Hammer and Wisner West zones 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. PGE mineralization is hosted within felsic and mafic gneiss of Levack Gneiss Complex and granite of the Cartier batholith (Fig. 2). Numerous 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, 2008). The Wisner West zone is situated in the footwall to a 12 km long embayment in the SIC (Bowell embayment), which is bound 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 (West Wisner zone, 750 x 2 km, trending southwest-northeast), which 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 PGE grades from the abundance of chalcopyrite characterizes this low-sulphide high-PGE mineralization at Wisner West (Ames and Kjarsgaard, 2013).

Approximately 3.5 km to the east, which is 1.3 km from the base of the SIC along the northern margin of the Joe Lake gabbroic intrusion, the Broken Hammer Cu-(Ni)-PGE occurrence, is hosted dominantly in felsic gneiss and granite within a 200 m wide zone of Sudbury breccia (Péntek et al., 2008). The Sudbury breccia zone trends southeast-northwest (330º), is subparallel in dip to the SIC, and hosts the main Big Boy Cu-PGE vein. The Broken Hammer occurrence was discovered in 2003 by surface prospecting for Cu-Ni-PGE sulphide veins. A stripped outcrop area was sampled for bedrock and till geochemical and mineralogical studies by the GSC in 2006. In the winter of 2011, much of the till and bedrock that was sampled in this study was removed during the digging of an open pit to collect a bulk sample for a pre-feasibility study of the Broken Hammer occurrence (Fig. 3). The Broken Hammer Zone is a shallow surface zone of vein- and vein stockwork-hosted copper-PGE mineralization (Fig. 3) within Sudbury breccia (Fig. 4) developed in

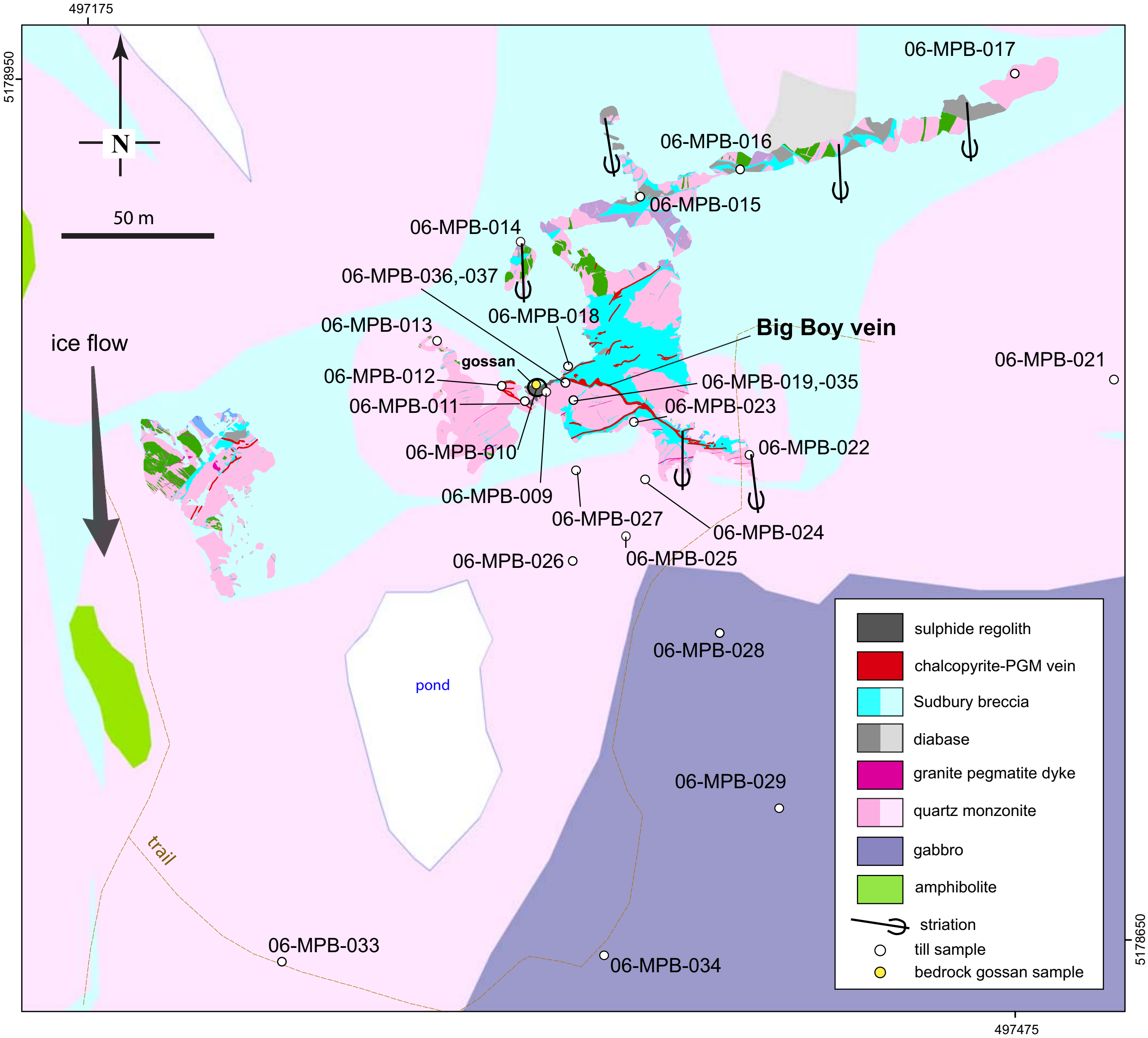


Figure 3. Detailed bedrock geology map of the Broken Hammer property exposed by stripping (dark colour shades) and superimposed on the regional bedrock geology (light colour shades), together with the location of GSC till samples and one gossan sample collected in 2006 proximal to the Big Boy chalcopyrite vein (detailed bedrock geology from Peterson et al. 2004; regional bedrock geology from Ames et al., 2005) (Datum NAD27).

the NeoArchean quartz-monzonite, Levack Gneiss Complex (Peterson et al., 2004; Péntek et al., 2008). New exposures in the pit revealed a "super" high-grade sperrylite zone comprising a hydrothermal assemblage of coarse epidote-quartz-sperrylite, which contained world-class sperrylite crystals as large as 13 mm (Wilson, 2012; Ames et al., 2013a).

The indicated mineral resource is 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 surface expression is a zone approximately 25 m x 250 m that plunges southwest below the Joe Lake gabbro and extends over 100 m. The main 2 to 120 cm wide en-echelon chalcopyrite Big Boy vein (Fig. 5) is dominanted by chalcopyrite-magnetite-millerite with numerous trace and rare precious metal minerals that occur as tellurides, bismuthides, selenides, and stannides (Table 1). A thin (cms) post-glacial gossan, which developed on part of the Cu-PGE vein (Fig. 3), was exposed on the stripped bedrock surface in 2006 (Fig. 6). This gossan contains abundant sperrylite, Se-galena, cassiterite, kotulskite, merenskyite, electrum, arsenopyrite, and native silver (Fig. 7). Trace elements in the mineral assemblages in

Figure 4. Photograph of Sudbury breccia showing pink xenoliths of gneiss in dark grey fine-grained matrix exposed at bedrock site 06-MPB-R010, which is located 66 m from the main chalcopyrite vein.

the weathered sulphide include Pd-Pt-Sn-Pb-Au-Ag-As-Bi-Te, and are reflected in the sulphide ore lithogeochemistry (Ames et al., 2006a,b, 2007; Péntek et al., 2008).

Surficial geology

The Sudbury region was most recently glaciated during the Late Wisconsin (25,000–10,000 years ago), when generally south-southwest-flowing ice of the Labrador Sector covered the region (Fig. 8) (Boissoneau, 1968; Bajc, 1997a,b,c; Bajc and Hall, 2000). In the Wisner Township area, till was deposited by ice flowing southward (185–175º). The local till on the North Range generally has a silty sand to sand matrix (Bajc and Hall, 2000) and is loose, thus making it an ideal sample medium for indicator mineral and till geochemical analyses. The Wisner Township area is dominated by

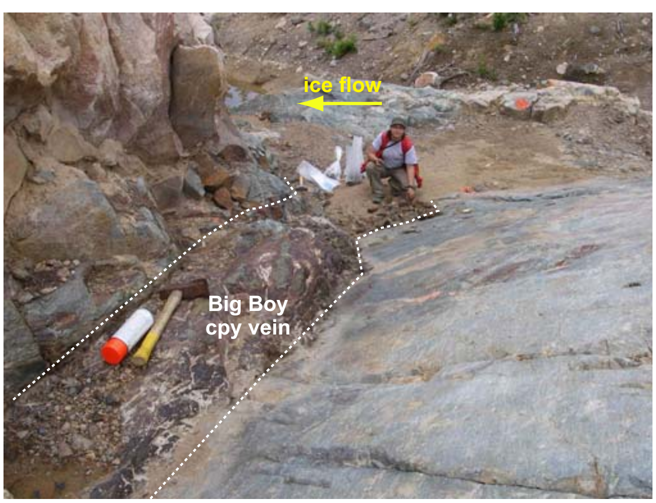


Figure 5. Photograph showing the Big Boy chalcopyrite vein exposed in a pre-2007 stripped area at the Broken Hammer occurrence. cpy = chalcopyrite

Table 1. Summary of ore mineralogy for the Broken Hammer Cu-(Ni)-PGE deposit (summarized from Mealin, 2005; Watkinson et al., 2005; Ames et al., 2006(b); Péntek et al., 2008; Kjarsgaard and Ames, 2010).

Mineral	Formula
Major and minor minerals in the ore	
chalcopyrite	$CuFeS_2$
millerite	NiS
Trace and rare minerals in the ore	
Zn-bearing minerals	
sphalerite	(Zn,Fe,Cd)S
Cu-bearing minerals	
bornite	Cu_5FeS_4
covellite	CuS
wittichenite	Cu_3BiS_3
emplectite	$CuBiS_2$
Sn-bearing mineral	
cassiterite	SnO_2
Fe-, Ni-bearing minerals	
pentlandite	$(Fe,Ni,Co)_9S_8$
melonite	$NiTe_2$
pyrite	FeS_2
violarite	$(Fe,Ni)_2S_4$
polydymite	$Ni^{2+}Ni_2^{3+}S_4$
As-, Pb-bearing minerals	
Se-galena	Pb(S,Se)
clausthalite	PbSe
arsenopyrite	FeAsS
Bi-, Te-bearing minerals	
tetradymite	Bi_2Te_2S
kawazulite	$Bi_2(Te,Se,S)_3$
Precious metal minerals (Ag, Au)	
hessite	Ag_2Te
naumannite	Ag_2Se
volynskite	$AgBiTe_2$
bohdanowiczite	$AgBiSe_2$
native silver	Ag
gold	Au
electrum	$Au_{65}Ag_{35}$
Platinum Group minerals (Pd, Pt)	
merenskyite	$(Pd)(Te,Bi)_2$
Pd-melonite	$(Ni,Pd)Te_2$
michenerite	(Pd,Pt)BiTe
sperrylite	$PtAs_2$
kotulskite	PdTe
sopcheite	$Ag_4Pd_3Te_4$
UM1	$CuBi(Pd,Ni)S_3$
malyshevite	$PdCuBiS_3$

Figure 6. Post-glacial gossan developed on the Big Boy chalcopyrite vein and exposed in 2006 in a stripped bedrock area: **a)** outline of gossanous area looking west across the stripped bedrock; **b)** gossan being sampled (site 06-MPB-010; for location see Fig. 3).

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 occurrence was overlain by 1 to 3 m of till. In general, till across the North Range is loose, thin (<0.5 to 3 m), locally-derived and has a silty sand (>50% sand) matrix that contains about 10 to 30% clasts. Soil has been developing on the glacial sediments of the North Range for about 10,000 years (i.e. since deglaciation), which has produced a podzolic soil (Barnett and Bajc, 2002).

Historically, till sampling has not been a component of mineral exploration in the Sudbury region, due to abundant bedrock outcrop and widespread surface contamination related to the mining and smelting operations in the region over the last 115 years. However, the North Range and west end of the Sudbury Structure have thicker and 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. As well, these areas to the west and north are 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.

Coker et al. (1990, 1991) sampled soil, till, and vegetation over two mineralized zones in the east and north parts of the Sudbury Structure, and reported that Ni, Cu, Au, and As in till, and to a lesser degree Sb, Se, Sr, Co, Pb, and Zn best reflect Ni-Cu-PGE mineralization. Bajc and Hall (2000) carried out both a regional-scale till geochemical survey of the North and West Range in the Sudbury Structure, as well as detailed studies at selected deposits/occurrences in support of Ni-Cu-PGE exploration, including footwall mineralization on the Barnet property. The authors demonstrated that till matrix geochemistry is a useful exploration method in the Sudbury region; however, they cautioned that the B-horizon developed on the till was depleted in metals compared 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.

The anthropogenic effects on till mineralogy and geochemistry within the Sudbury area are a concern. The region has been affected by atmospheric contamination related to the smelting of ore since the late 1800s (e.g. Adamo et al., 1996; Gratton et al., 2000;

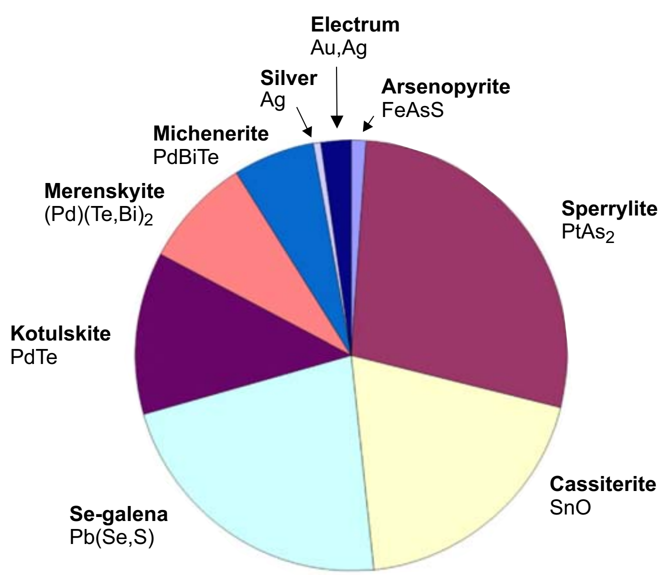


Figure 7. Relative abundance of Pt-Pd-As-Sn minerals in a 1 kg sample of post-glacial gossan developed on the Big Boy chalcopyrite vein (n=180 mineral grains).

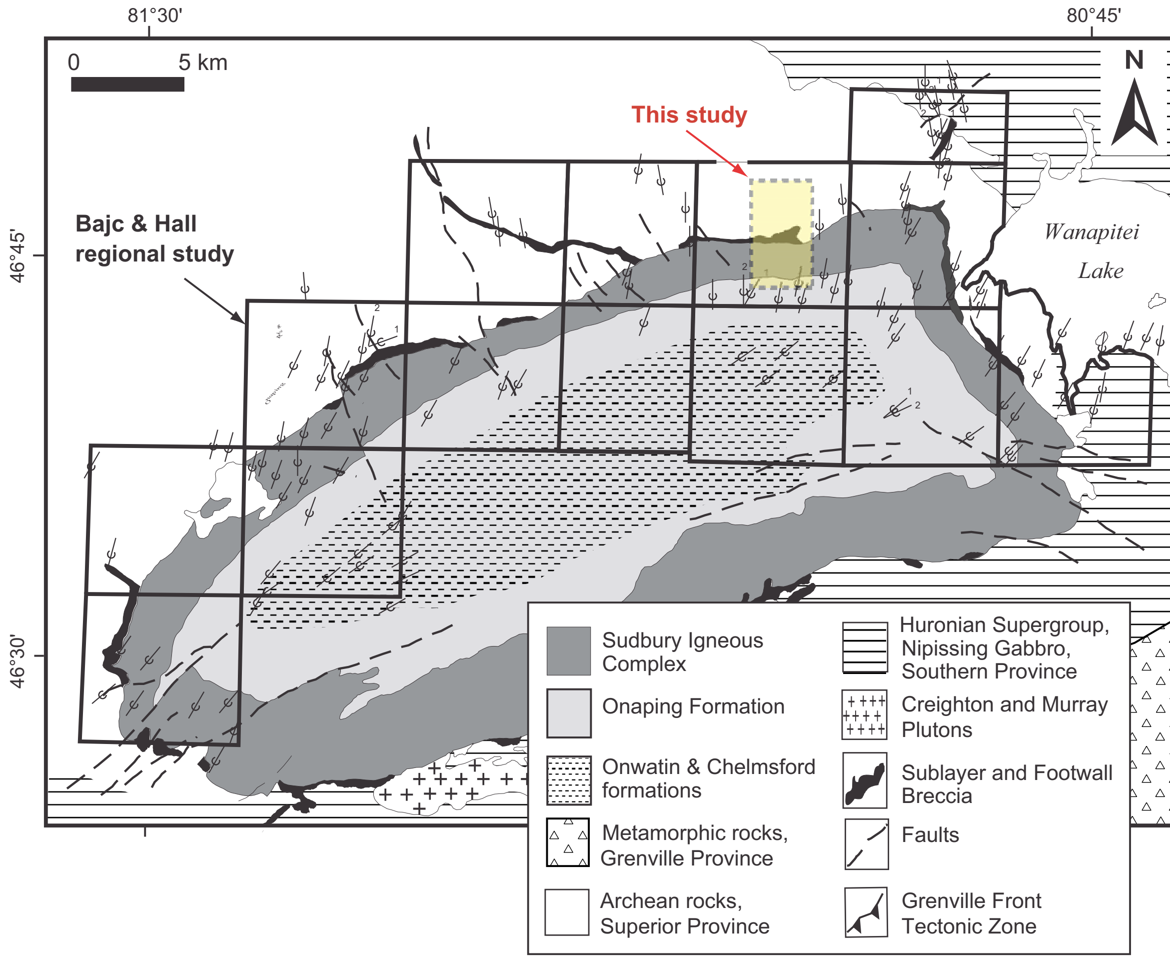


Figure 8. Late Wisconsin regional ice-flow patterns in the Sudbury region (modified from Bajc and Hall, 2000).

Barnett and Bajc, 2002; Winterhalder, 2002). Bajc and Hall (2000), however, demonstrated that airborne contamination in soils in the North Range is limited to the upper organic horizon (humus) and has not affected the B- or C-horizons of the soil profile developed on till. For this study, humus was not sampled, only the B- or C-horizons developed in till.

METHODS

Field sampling

A total of 38 till samples were collected in 2006 (Figs. 2, 3) around the Broken Hammer occurrence for indicator mineral and matrix geochemical analyses. Sites included sections exposed along the main stripped outcrop containing the subcropping surface of the Big Boy vein (samples 06-MPB-009,-011,-012,-018,-019, -035,-036, and -037) (Fig. 9), and along associated stripped outcrops or clearings nearby 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 occurrence (samples 06-MPB-028, -029, -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 to compare till geochemical signatures with similar mineralization styles. Two till samples down-ice of the Broken Hammer occurrence, collected by Bajc and Hall (2000), were re-analyzed with the GSC till samples: samples 93-AFB-037 (relabeled as 06-MPB-073) and 93-AFB-038 (relabeled as 06-MPB-074).

Sample sites were selected to characterize the mineralogical and geochemical signature of mineralization at varying distances down-ice, not to define a dispersal train from the Broken Hammer occurrence. 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, field descriptions, and individual site photos are included in Appendix A1 and A2. 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 A1.

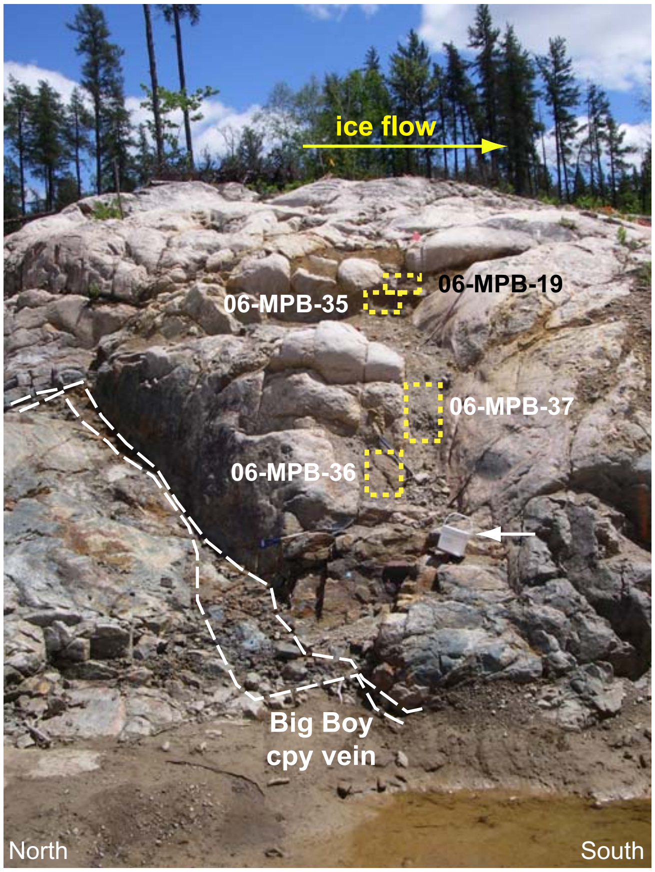


Figure 9. Till sample sites 06-MPB-019, -035, -036, and -037, just down-ice of the Big Boy chalcopyrite vein. (cpy= chalcopyrite)

Grain size and matrix carbonate analysis

The percentages of clay (<0.002 mm), silt (0.002–0.63 mm), and sand (0.63–2.0 mm) in the matrix fraction of till samples were determined at the GSC Sedimentology Lab in Ottawa using a combination of sieving and the Lecotrac LT-100 particle size analyzer (Girard et al., 2004). Total carbonate contents of the matrix fraction were also determined at GSC Sedimentology Lab, Ottawa, using the Chittick gasometric method (Dreimanis, 1962). Grain-size and carbon data are listed in Appendix B.1.

Geochemical analysis

A split of each of the 38 till samples that were collected in 2006 and the two previously collected OGS till samples were submitted to ACME Labs, Vancouver for analysis of the <0.063 mm size fraction after sample drying and sieving at the GSC Sedimentology Laboratory, Ottawa. Major oxides and several minor elements were determined by ICP-ES and rare earth elements, and refractory elements were determined by ICP-MS; both following a lithium meta/tetraborate fusion and nitric acid digestion on a 0.2 g aliquot (Group 4A and 4B methods). In addition, a separate 0.5 g split was digested in aqua regia (3 ml 2-2-2 HCl-HNO_3-H_2O at 95ºC for one hour, diluted to 10 ml) and analyzed by ICP-MS to determine base and precious metals (Group 1F method). The elements Au, Pt, and Pd were determined by Pb-collection fire assay ICP-MS (Hall and Bonham-Carter, 1988; Hall and Oates, 2003) on 30 g aliquots (Group 3B method).

Analytical accuracy and precision was monitored by including CANMET certified reference standards (https://www.nrcan.gc.ca/mining-materials/certified-reference-materials/7827) in the analytical batch. CANMET standards UM-2 and UM-4 were analyzed 5 times each, and TDB-1 was analyzed two times, for a total of 12 analysis or 11% of the sample batch. Six preparation duplicates, also referred to as ‘blind’ duplicates, and 13 analytical duplicates were also analyzed. Geochemical data for till samples and quality assurance/quality control (QA/QC) samples are listed in Appendix B2, B3, and B4. Recommended values for the CANMET standards are highlighted in red in each appendix listing of the QA/QC data. Based on evaluations of the reported QA/QC data, all analytical data were deemed acceptable.

Organic and inorganic carbon content and loss on ignition (LOI) were determined at the GSC Sedimentology Lab, Ottawa, and the results are reported in Appendix B1. Organic and inorganic carbon were determined using the LECO method at 1350ºC. Loss on ignition was determined after combustion at 500ºC for 1 hour.

Heavy mineral processing and indicator mineral recovery

Large till samples (~15 kg) were processed at Overburden Drilling Management Ltd. (ODM), Ottawa, to produce a non-ferromagnetic heavy mineral concentrate for picking indicator minerals. Methods used are described 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. This fraction was then micropanned to recover gold, sulphide, and platinum group minerals in the <2 mm fraction. These panned minerals were examined, counted, and then returned to the sample. 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 then 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 grain counts reported in Table 2 are the result of this step. Complete listings of indicator mineral data for bedrock and till samples from this study are reported in McClenaghan and Ames (2013).

Data plotting

Prior to calculation of statistics and plotting of data, all geochemical values reported as less than the lower detection limit were reassigned values of one half the element's detection limit (Appendix B2, B3). Correlation coefficients and scatter plots were then calculated for the 38 GSC till samples and the two OGS till samples (samples 93-AFB-037 and -038) that were re-analyzed using the Macintosh program Aabel version 2.4 (Table 3). Correlation coefficients for the aqua regia data set were calculated using log transformed values and are reported in Table 3.

Geochemical maps of the Broken Hammer area were plotted for Pd, Pt, Au, Cu, Ni, Ag, Bi, Cd, Te, and Sb for the 24 till samples sampled closest to mineralization (Appendix C, maps 1 to10). Geochemical maps of Pt, Pd, and Au across the Broken Hammer and Wisner West region were plotted (Appendix D, maps 11 to 13). The concentrations of Pd, Pt, Au, Cu, and Ni

Table 2. Select element concentrations determined by FA-ICP-MS (Pt, Pd, Au), borate fusion (Sn), and aqua regia/ICP-MS for the <0.063 mm fraction of till from the Broken Hammer study area (n=38) and ranked according to distance from mineralization. Also reported are the number of sperrylite, chalcopyrite, and gold grains (normalized to 10 kg sample weight) recovered from the <0.25 mm non-ferromagnetic heavy mineral fraction of till.

Sample Number	Distance measured relative to	Interpretation	Degree of till of oxidation	Distance (m) down-ice of Broken Hammer mineralization	Direction from Broken Hammer	Sperrylite grains/ 10 kg	Chalcopyrite grains/ 10 kg	Gold grains/ 10 kg	Au ppb	Pt ppb	Pd ppb	Pt/ (Pt+Pd)
06-MPB-001	Broken Hammer	background	strong	-6000	N	0	0	12	3	3.4	3.5	0.49
06-MPB-002	Broken Hammer	background	strong	-6000	N	0	0	4	4	2.5	2.2	0.53
06-MPB-003	Broken Hammer	background	moderate	-6000	N	0	0	28	6	1.5	1.6	0.48
06-MPB-020	Broken Hammer	background	strong	-250	NE	0	0	11	2	1.1	1.7	0.39
06-MPB-017	Broken Hammer	background	weak	-120	NE	0	0	2	2	1.1	0.7	0.61
06-MPB-014	Broken Hammer	background	moderate	-45	N	0	0	5	4	2.1	6.5	0.24
06-MPB-016	Broken Hammer	background	strong	-40	NE	0	0	5	2	0.7	3.1	0.18
06-MPB-015	Broken Hammer	background	strong	-25	N	0	0	4	2	1.0	4.0	0.20
06-MPB-018	Broken Hammer	overlying	weak	0	N	12	145	30	3	2.7	7.6	0.26
06-MPB-011	Broken Hammer	overlying	moderate	0	NA	714	10714	456	97	245	509	0.32
06-MPB-012	Broken Hammer	overlying	strong	0	NA	213	15957	68	70	175	429	0.29
06-MPB-009	Broken Hammer	proximal down-ice	weak	1	NA	2	5	3	5	7.7	20.8	0.27
06-MPB-036	Broken Hammer	proximal down-ice	weak	1	S	10	5	10	7	4.2	15.3	0.22
06-MPB-037	Broken Hammer	proximal down-ice	weak	1	S	7	5	2	4	7.7	10.2	0.43
06-MPB-023	Broken Hammer	proximal down-ice	moderate	4	S	10	5	17	4	3.0	12.2	0.20
06-MPB-022	Broken Hammer	proximal down-ice	moderate	4	E	8	3	3	7	2.9	2.1	0.58
06-MPB-019	Broken Hammer	proximal down-ice	weak	6	S	11	91	13	35	15	23.0	0.39
06-MPB-035	Broken Hammer	proximal down-ice	weak	6	S	25	100	35	10	29	26.8	0.52
06-MPB-013	Broken Hammer	proximal down-ice	moderate	12	W	4	0	6	9	26	59.0	0.31
06-MPB-024	Broken Hammer	proximal down-ice	strong	25	S	13	5	18	3	2.3	1.8	0.56
06-MPB-025	Broken Hammer	proximal down-ice	strong	40	S	29	6	34	15	8.2	8.2	0.50
06-MPB-026	Broken Hammer	proximal down-ice	strong	40	S	25	10	32	8	5.9	5.8	0.50
06-MPB-027	Broken Hammer	proximal down-ice	strong	45	S	57	22	32	21	30	12.0	0.71
06-MPB-028	Broken Hammer	proximal down-ice	strong	60	S	0	4	11	3	3.7	11.9	0.24
06-MPB-029	Broken Hammer	proximal down-ice	strong	120	S	0	4	6	4	2.6	2.6	0.50
06-MPB-021	Broken Hammer	proximal down-ice	moderate	125	E	0	0	3	2	5.3	5.4	0.50
06-MPB-034	Broken Hammer	proximal down-ice	strong	170	S	0	4	5	5	4.2	4.2	0.50
06-MPB-033	Broken Hammer	proximal down-ice	strong	225	S	2	3	16	3	5.2	2.7	0.66
06-MPB-032	Broken Hammer	proximal down-ice	strong	250	S	1	0	2	7	2.3	4.5	0.34
06-MPB-031	Broken Hammer	down-ice	strong	600	S	21	0	9	2	2.6	1.9	0.58
06-MPB-038	Broken Hammer	down-ice	weak	1500	S	0	0	0	3	4.5	3.9	0.54
06-MPB-030	Broken Hammer	down-ice	weak	1800	SE	0	0	3	7	0.8	1.3	0.38
06-MPB-008	Broken Hammer	down-ice	strong	5000	S	4	0	2	2	2.1	1.9	0.53
06-MPB-039	Broken Hammer	down-ice	weak	5000	SE	0	0	0	5	3.8	6.4	0.37
06-MPB-004	Wisner West	NA	moderate	NA	NA	0	0	5	5	1.0	2.2	0.31
06-MPB-005	Wisner West	NA	moderate	NA	NA	0	0	1	3	1.2	1.1	0.52
06-MPB-006	Wisner West	NA	moderate	NA	NA	0	43	1	4	6.6	4.5	0.59
06-MPB-007	Wisner West	NA	moderate	NA	NA	0	0	1	5	2.8	2.1	0.57

were plotted as proportional dots using ArcGIS v.8. Values corresponding to approximately the 50th, 75th, 90th, and 95th percentiles were used as thresholds for dot sizes. Percentiles for both map scales were calculated using data from this study (n=38) plus data for till samples within a 7 km radius of Broken Hammer (n=35) reported by Bajc and Hall (2000).

RESULTS

Till texture and total carbonate content

Till matrix texture and organic carbon content data are listed in Appendix B.1. In general, till sampled in this study commonly has a silty sand matrix, containing on average 1% clay, 30% silt, and 69% sand (Fig. 10). The till matrix does not contain detectable carbonate (Chittick method). Values for organic carbon vary from 0.1 to 2.3% and LOI values vary from 0.8 to 7.6 %.

Till geochemistry of the <0.063 mm fraction

The distribution of trace elements in the <0.063 mm fraction of till around the Broken Hammer occurrence are shown on maps in Appendix C. The regional till survey of the Sudbury North Range by Bajc and Hall (2000) provides the regional context in which to interpret the Broken Hammer and Wisner West till geochemical data. Table 4 lists the 95th percentile values for Bajc and Hall's (2000) regional till samples, both oxidized and unoxidized, as well as the highest values reported in this study.

Table 2 continued.

Sample Number	Mo ppm	Cu ppm	Ni ppm	Cu/ (Cu+Ni)	Pb ppm	Zn ppm	Ag ppb	Co ppm	As ppm	Cd ppm	Sb ppm	Bi ppm	Cr ppm	Ba ppm	Tl ppm	S ppm	Hg ppb	Se ppm	Te ppm	Mn ppm	Fe %	Sn ppm (total)
06-MPB-001	0.5	115	50	0.70	14	59	25	19.7	1.8	0.07	0.04	0.16	74.0	124.1	0.28	0.02	31	0.2	<.02	385	2.99	3
06-MPB-002	0.7	152	57	0.73	54	133	27	24.1	2.9	0.21	0.06	0.34	115.7	136.5	0.49	0.01	18	0.2	0.02	483	3.42	4
06-MPB-003	0.6	56	28	0.67	15	41	23	13.5	2.6	0.07	0.04	0.24	38.9	29.6	0.12	0.02	8	0.1	<.02	248	1.88	1
06-MPB-020	0.8	39	41	0.49	9	51	14	15.4	0.9	0.12	0.03	0.06	85.2	37.1	0.11	0.04	44	0.5	<.02	250	3.09	3
06-MPB-017	0.3	44	19	0.69	7	29	3	12.0	1.0	0.05	0.03	0.09	27.5	31.9	0.11	0.02	6	0.3	0.02	198	1.96	3
06-MPB-014	0.4	53	26	0.67	12	41	8	14.5	1.2	0.07	0.03	0.11	35.8	31.5	0.14	0.01	22	0.2	<.02	234	2.43	14
06-MPB-016	0.7	36	21	0.64	7	33	6	10.0	0.7	0.06	0.04	0.08	37.6	19.8	0.09	0.03	31	0.4	<.02	188	2.34	3
06-MPB-015	0.4	108	21	0.84	19	30	6	7.9	1.2	0.08	0.03	0.08	31.7	16.3	0.07	0.02	25	0.3	0.02	160	2.08	3
06-MPB-018	0.2	324	108	0.75	9	38	10	12.1	0.9	0.11	0.03	0.14	32.2	35.6	0.13	0.01	<5	0.2	0.02	241	2.19	2
06-MPB-011	0.4	3454	344	0.91	21	43	147	12.3	1.5	0.29	0.21	3.57	39.2	36.6	0.14	0.01	6	1.0	1.76	223	2.44	5
06-MPB-012	0.6	1182	101	0.92	15	43	159	11.0	1.7	0.11	0.05	2.50	39.8	39.7	0.15	0.03	16	1.0	2.09	226	2.93	7
06-MPB-009	0.3	231	31	0.88	10	32	15	10.8	1.0	0.07	0.03	0.18	28.2	29.2	0.10	0.01	<5	0.3	0.04	206	2.01	2
06-MPB-036	0.4	168	30	0.85	17	36	16	10.6	0.9	0.11	0.03	0.22	28.4	32.3	0.11	0.01	6	0.2	0.04	204	2.12	2
06-MPB-037	0.3	97	30	0.76	10	38	9	12.3	1.0	0.07	0.02	0.16	28.6	33.9	0.11	0.01	8	0.2	0.03	216	2.18	2
06-MPB-023	0.6	728	74	0.91	24	44	98	12.2	1.2	0.14	0.03	0.33	52.2	29.1	0.09	0.07	47	0.5	0.05	213	2.79	2
06-MPB-022	0.4	115	28	0.80	7	26	115	7.0	0.7	0.04	0.04	0.12	30.5	31.7	0.08	0.05	24	0.4	<.02	150	1.67	3
06-MPB-019	0.2	272	47	0.85	11	31	14	10.6	0.9	0.10	0.03	0.27	26.5	32.8	0.11	0.02	<5	0.3	0.08	217	1.95	3
06-MPB-035	0.4	338	45	0.88	10	35	10	10.7	1.0	0.10	0.03	0.34	31.4	32.4	0.11	0.01	5	0.4	0.07	230	2.07	2
06-MPB-013	0.6	757	133	0.85	14	51	14	20.5	1.6	0.15	0.13	0.45	47.3	60.0	0.31	0.01	<5	0.2	0.09	317	2.70	4
06-MPB-024	0.4	63	27	0.70	8	32	11	9.5	1.3	0.11	0.03	0.13	40.6	21.0	0.06	0.05	45	0.4	<.02	171	2.23	3
06-MPB-025	0.4	190	33	0.85	8	36	6	9.2	0.7	0.06	0.03	0.20	38.0	22.7	0.09	0.03	18	0.3	0.04	194	2.26	3
06-MPB-026	0.8	233	42	0.85	15	47	14	13.6	1.8	0.11	0.03	0.23	50.7	29.1	0.09	0.07	60	0.6	0.04	203	2.74	2
06-MPB-027	0.6	242	37	0.87	10	39	15	10.0	1.2	0.11	0.04	0.29	47.3	21.1	0.07	0.04	24	0.4	0.11	206	2.61	3
06-MPB-028	0.4	66	27	0.71	10	38	20	11.3	1.6	0.11	0.04	0.14	41.3	34.5	0.09	0.04	46	0.4	<.02	200	2.43	2
06-MPB-029	0.4	54	28	0.66	9	37	11	11.4	1.2	0.13	0.04	0.10	33.4	43.0	0.08	0.05	32	0.4	0.03	203	2.51	5
06-MPB-021	0.5	166	28	0.85	7	35	5	11.9	1.4	0.07	0.04	0.15	34.6	36.9	0.11	0.03	10	0.2	0.03	220	2.25	1
06-MPB-034	0.6	95	39	0.71	13	51	10	13.0	1.5	0.12	0.03	0.18	55.3	32.0	0.09	0.02	32	0.5	0.04	236	2.97	5
06-MPB-033	0.6	67	35	0.66	10	55	11	15.1	1.1	0.10	0.03	0.11	44.6	31.4	0.11	0.02	43	0.4	<.02	244	3.05	4
06-MPB-032	0.6	53	26	0.67	9	39	19	11.2	1.1	0.08	0.04	0.11	41.2	25.4	0.12	0.06	43	0.4	<.02	174	2.14	4
06-MPB-031	0.4	56	31	0.65	7	39	10	14.8	0.9	0.06	0.03	0.11	45.1	28.6	0.06	0.03	44	0.4	0.02	185	2.71	2
06-MPB-038	0.4	69	23	0.75	8	39	8	15.0	1.3	0.06	0.03	0.08	34.9	46.3	0.13	0.01	<5	0.1	<.02	245	2.31	1
06-MPB-030	0.3	32	16	0.66	6	18	6	7.7	1.2	0.03	0.04	0.09	24.4	24.9	0.06	<.01	6	0.2	<.02	163	1.39	2
06-MPB-008	1.8	60	66	0.48	76	196	38	24.3	11.2	0.23	0.08	0.07	61.3	23.0	0.12	0.02	39	0.3	<.02	432	2.85	4
06-MPB-039	1.1	80	63	0.56	59	235	21	21.8	2.4	0.67	0.11	0.11	46.0	57.4	0.16	0.01	<5	<.1	<.02	365	2.92	4
06-MPB-004	0.6	47	22	0.68	16	43	15	12.0	1.1	0.07	0.02	0.09	32.2	44.0	0.15	0.03	26	0.2	<.02	203	2.28	2
06-MPB-005	0.5	44	24	0.65	11	40	10	16.6	1.0	0.05	0.02	0.10	33.8	50.6	0.17	0.02	13	0.2	<.02	256	2.37	2
06-MPB-006	0.3	188	54	0.78	15	50	26	18.6	1.3	0.06	0.02	0.12	45.7	65.4	0.19	0.01	16	0.2	0.05	307	2.72	3
06-MPB-007	0.6	115	83	0.58	21	65	19	25.1	1.6	0.12	0.04	0.11	59.6	53.4	0.16	0.01	13	0.4	0.03	276	2.86	3

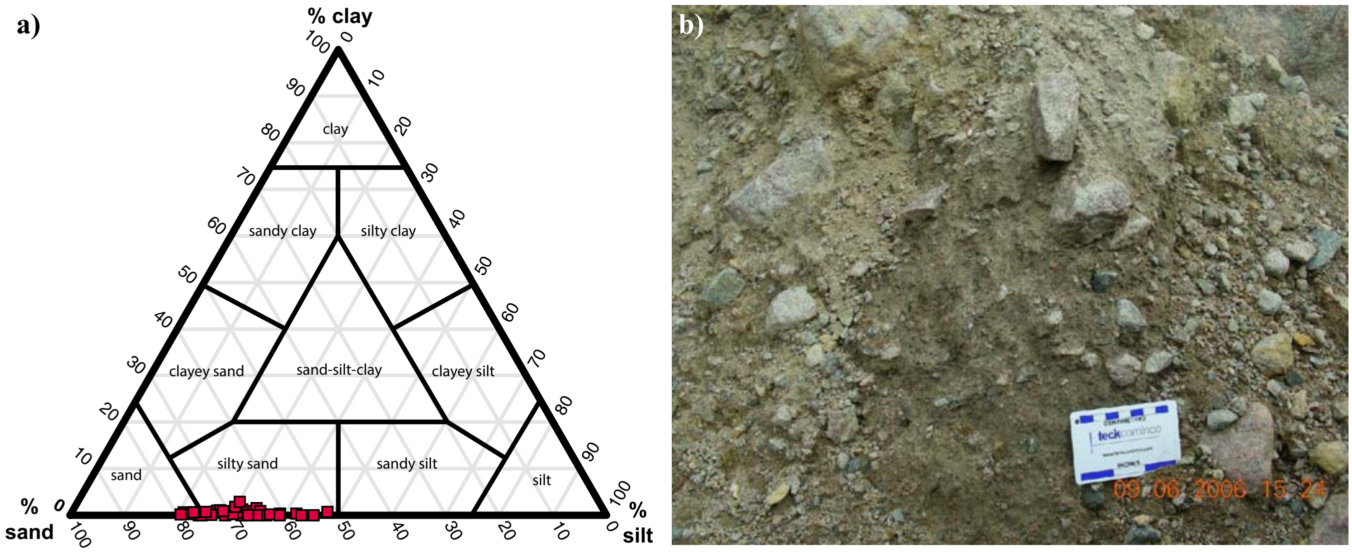


Figure 10. a) Ternary plot of the percentage of clay, silt, and sand in the till matrix (n=38); **b)** close-up of sandy till at sample site 06-MPB-009, which is typical of the deposit area.

Platinum, palladium, and gold

Palladium values in till are generally higher than Pt values around the Broken Hammer occurrence. Platinum values range from 0.7 to 245 ppb and Pd values range from 0.7 to 509 ppb. Till samples up ice of the occurrence (Table 2) contain between 0.7 and 3.4 ppb Pt and between 0.7 and 6.4 ppb Pd. Platinum (3.7 to 245 ppb) and Pd (10 to 509 pb) values are highest in till samples collected between 0 and 60 m south (sample 06-MPB-028) of the Big Boy chalcopyrite vein (Appendix C: maps 1, 2). Sample 06-MPB-13, collected 25 m west of the main chalcopyrite vein also has elevated values of Pt (26.2 ppb) and Pd (59.0 ppb). At a regional scale, Pt and Pd values are highest in till samples around the Broken Hammer and Wisner West occurrences Appendix D, maps 11 and 12). In addition, Pt values are slightly elevated (4.5 ppb) in sample 06-MPB-038, 1.5 km SW of Broken Hammer.

Concentrations of Pd and Pt exhibit strong (r>0.8) correlations with each other (Fig. 11) as well as with Au (Fig. 11), Cu, Bi, and Te, and significant (r=0.6-0.8) correlations with Ni (Table 3). Pt/(Pt+Pd) ratios for till

Table 3. Correlation matrix of selected log transformed elements determined by FA-ICP-MS (Pt, Pd, Au), borate fusion (Sn), and aqua regia/ICP-MS for the <0.063 mm fraction of till from the Broken Hammer study area (n=38). Strong correlation: r >0.8 (bold red), significant correlation: r = 0.6-0.8 (bold black).

	Au	Pt	Pd	Cu	Pb	Zn	Ag	Ni	Co	As	Cd	Sb	Bi	Mo	Mn	Fe	Tl	S	Hg	Se	Te	Ga
Au	1.00																					
Pt	**0.82**	1.00																				
Pd	**0.78**	**0.90**	1.00																			
Cu	**0.71**	**0.85**	**0.87**	1.00																		
Pb	0.06	0.09	0.13	0.23	1.00																	
Zn	-0.13	0.02	-0.05	0.01	**0.86**	1.00																
Ag	0.52	0.48	0.50	0.57	0.46	0.28	1.00															
Ni	0.52	**0.67**	**0.66**	**0.80**	0.49	0.42	**0.63**	1.00														
Co	-0.23	-0.02	-0.13	-0.02	**0.63**	**0.81**	0.13	0.43	1.00													
As	-0.06	0.04	-0.03	0.02	**0.76**	**0.74**	0.31	0.32	**0.61**	1.00												
Cd	0.22	0.35	0.37	0.38	**0.75**	**0.76**	0.39	**0.66**	0.49	0.54	1.00											
Sb	0.39	0.44	0.46	0.44	0.47	0.46	0.44	**0.66**	0.29	0.49	**0.66**	1.00										
Bi	**0.83**	**0.87**	**0.86**	**0.88**	0.19	-0.01	**0.61**	**0.70**	-0.06	0.09	0.35	0.50	1.00									
Mo	-0.16	-0.10	-0.15	-0.15	0.59	**0.73**	0.25	0.13	0.50	**0.65**	0.51	0.36	-0.07	1.00								
Mn	-0.11	0.09	0.00	0.10	**0.71**	**0.84**	0.21	0.47	**0.89**	**0.69**	0.54	0.37	0.08	0.47	1.00							
Fe	-0.08	0.19	0.11	0.17	0.53	**0.70**	0.26	0.47	**0.72**	0.40	0.59	0.22	0.15	0.59	**0.65**	1.00						
Tl	0.07	0.17	0.15	0.24	0.51	0.54	0.24	0.46	**0.72**	0.36	0.32	0.32	0.25	0.19	**0.80**	0.47	1.00					
S	-0.13	-0.21	-0.23	-0.16	-0.21	-0.16	0.12	-0.23	-0.25	-0.09	-0.15	-0.22	-0.14	0.25	-0.34	0.15	-0.35	1.00				
Hg	-0.27	-0.29	-0.33	-0.31	0.01	0.06	0.13	-0.23	-0.04	0.09	-0.08	-0.23	-0.22	0.43	-0.15	0.38	-0.27	**0.74**	1.00			
Se	0.37	0.39	0.37	0.38	-0.18	-0.29	0.35	0.27	-0.31	-0.17	0.00	0.05	0.43	0.01	-0.37	0.17	-0.32	0.47	0.50	1.00		
Te	**0.81**	**0.89**	**0.86**	**0.87**	0.10	-0.09	0.48	**0.67**	-0.11	-0.02	0.29	0.38	**0.90**	-0.16	-0.03	0.15	0.10	-0.13	-0.23	0.54	1.00	
Ga	-0.19	0.09	0.01	0.06	0.42	**0.64**	0.20	0.33	0.56	0.29	0.54	0.14	-0.03	**0.61**	0.49	**0.91**	0.28	0.27	0.49	0.22	0.01	1.00

Table 4. Comparison of highest values reported for the <0.063 mm fraction of metal-rich till proximal to the Broken Hammer occurrence and the 95th percentile values for weathered (B horizon) and unweathered (C horizon) till in the Sudbury North Range region as reported by Bajc and Hall (2000). Methods: FA-ICP-MS (Pt, Pd, Au) and aqua regia/ICP-MS.

Element	Unoxidized Till 95th percentile Bajc & Hall (2000)	Oxidized Till 95th percentile Bajc & Hall (2000)	Highest value, this study
Cu (ppm)	193	90	3453
Ni (ppm)	97	75	344
Pt (ppb)	2.8	1.2	245
Pd (ppb)	3.2	1.2	509.0
Au (ppb)	29.5	9.9	97
Ag (ppm)	0.5	0.6	159 (ppb)
Cr (ppm)	91	71	85
Co (ppm)	28	18	25
As (ppm)	10.3	6.0	7.7
Sb (ppm)	0.5	0.6	0.21
Bi (ppm)	0.6	0.6	3.57
Se (ppm)	0.4	0.6	1.0
Te (ppm)	0.2 (90th)	0.4	2.09
Pb (ppm)	27	24	76

samples are listed in Table 2. Values range from 0.18 to 0.71, with the lowest values (<0.33) from metal-rich till proximal to mineralization.

Gold content in till around Broken Hammer varies from 2 to 97 ppb, with most values <5 ppb. Till samples up-ice contain between 2 and 6 ppb Au (Table 2). Six till samples proximal to mineralization contain elevated (10–97 ppb) Au contents (Appendix C, map 3). In addition to the elevated Au contents in till at Broken Hammer, Au values are elevated in two OGS till samples collected 8 km northwest and southwest of Broken Hammer (Appendix C, map 13). Gold displays strong correlations with Pt, Bi, and Te, and significant correlations with Pd and Cu (Table 3).

Copper and nickel

Aqua regia (AR) Cu values in till vary from 32 to 3454 ppm (Table 2). Background Cu contents in till up-ice vary between 36 and 152 ppm Cu. The highest Cu values in till are from samples collected <60 m down-ice of the main chalcopyrite vein and in sample 06-MPB-013, collected 25 m west of the known western extent

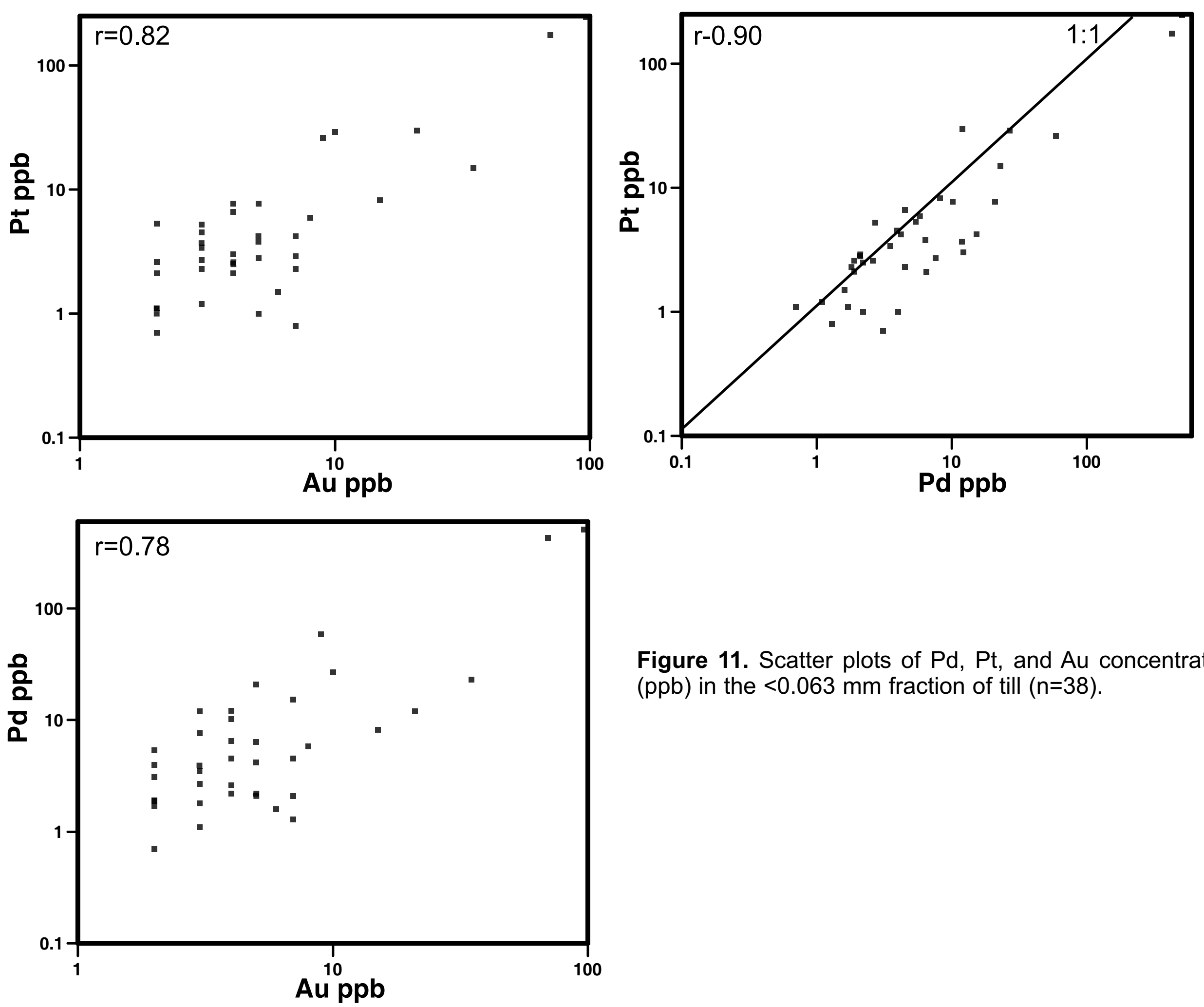


Figure 11. Scatter plots of Pd, Pt, and Au concentrations (ppb) in the <0.063 mm fraction of till (n=38).

of the main chalcopyrite vein (Appendix C, map 4). Copper abundance in till is strongly correlated with Pt, Pd, Bi, and Te, and significantly correlated with Ni and Au (Table 3). Ni-AR concentrations in till vary from 16 to 344 ppm, with the highest values in till closest to the chalcopyrite vein (Appendix C, map 5) and in sample 06-MPB-013 to the west. Nickel abundance displays significant correlations with Pd and Pt, as well as Cu, Ag, Cd, Sb, Bi, and Te (Table 3). The Cu/(Cu+Ni) ratios for till samples are listed in Table 2. Ratios vary from 0.56 to 0.92, with the highest values (>0.80) in the metal-rich till samples collected <60 m down-ice of mineralization.

Other elements

Till samples in this study contain on average 1 to 3 ppm Sn, as determined by borate fusion. However, sample 06-MPB-12, which was collected overlying the main vein, and sample 06-MPB-14, which was collected 45 m north of the main vein, contain elevated abundances (7–14 ppm) of Sn (Table 2).

The highest concentrations of Ag (159 ppb), Cd (0.29 ppm), Sb (0.21 ppm), Bi (3.57), Te (2.09 ppm), and Se (1.0 ppm), as determined by AR, are in till samples 06-MPB-011 and -012, collected closest to the Big Boy vein (Table 2; Appendix C, maps 6 to 10). These samples were expected to contain the most metal-rich debris as they are <2 m down-ice of the main chalcopyrite vein. A post-glacial gossan on the vein near the till samples yielded significant platinum group- and precious metal minerals (Fig. 7) (Ames et al., 2007). Elevated Ag values (>95 ppb) were also reported for till samples 06-MPB-022 and -023, collected <4 m from the main vein.

Silver, Cd, Sb, Bi, Se, and Te display multi-element correlations with one another. As shown in Table 3, Ag has a significant correlation with Ni and Bi, and Cd has a significant correlation with Pb, Zn, Ni, and Sb. Bismuth is strongly correlated with Au, Pt, Pd, Cu, and Te, and significantly with Ag and Ni. Tellurium displays strong correlations with Au, Pt, Pd, Cu, and Bi, and significant correlations with Ni. Selenium in till does not display any significant correlations with the ore-forming elements. Antimony shows significant correlations only with Ni and Cd.

The highest Tl-AR values reported in this study are from till samples 06-MPB-013 (0.31 ppm), 06-MPB-001 (0.28 ppm), and 06-MPB-002 (0.49 ppm). Thallium displays significant correlations with Co and Mn (Table 3).

Sites distal to the Broken Hammer occurrence

Till samples 06-MPB-005 and 06-MPB-006 were collected on the Wisner West property. Sample 06-MPB-006 contains elevated Pt (6.6 ppb) and Cu (188 ppm) concentrations (Table 2), as well as a significant number of visible chalcopyrite grains (43 grains/10 kg). Till sample 06-MPB-008, collected 5 km south of the Broken Hammer occurrence, contains elevated levels of Mo, Zn, As, and Cd (Table 2). Sample 06-MPB-039, collected 4 km southeast of the deposit, contains elevated concentrations of Mo, Pb, Zn, and Cd (Table 2). Both samples overlie the Onaping Formation and were collected to determine down-ice background concentrations. Sample 06-MPB-002 was collected 6 km north of the Broken Hammer occurrence and contains elevated concentrations of Zn, Cd, Tl, and Cr. The locations of these samples are shown on Figure 2.

Indicator mineral grain counts

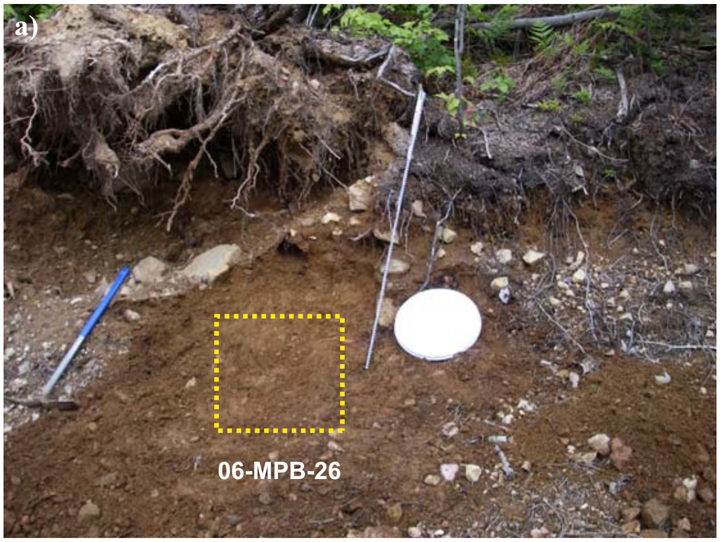
Counts of visible gold, sperrylite, and chalcopyrite grains in the heavy mineral fraction of till, normalized to a 10 kg sample weight, are listed in Table 2 and are plotted as proportional dot maps in Appendix E (maps 14 to 16). Background visible gold grain counts in till samples up-ice (north), defined using regional data of Bajc and Hall (2000), are <4 grains/10 kg. Metal-rich till proximal (<60 m down-ice) to the Broken Hammer occurrence contains between 2 and 456 gold grains/10 kg (Appendix E, map 14). Proximal till also contains between 0 and 714 sperrylite grains/10 kg, as compared to background counts of zero grains reported by Bajc and Hall (2000) (Appendix E, map 15). Chalcopyrite is by far the most abundant ore mineral in till down-ice of the occurrence, with up ~16,000 grains/10 kg in metal-rich till. The background abundance of chalcopyrite in regional till up-ice, as reported by Bajc and Hall (2000), is zero (Appendix E, map 16).

DISCUSSION

Till texture and carbon content

Till in the Broken Hammer region has a relatively uniform texture, containing on average 1% clay, 30% silt, and 69% sand. This high-sand/low-clay content of the till is typical of tills from the region (e.g. Bajc and Hall, 2000).

Loss on ignition values strongly correlate with organic carbon content, having a correlation coefficient of r=0.96. The highest values for organic carbon (>0.5 %) and LOI (>1.5 %) in till correspond to those samples reported as moderate to strongly oxidized (Appendix A1), based on their colour (orangey brown to medium brown) in the field (Fig. 12). Oxidized till was sampled at some sites because the till was thin (<2 m) and it was the only material available for sampling. These higher values for organic carbon and LOI are typical of B-horizon podzolic soil that has developed on a sandy, well drained till.



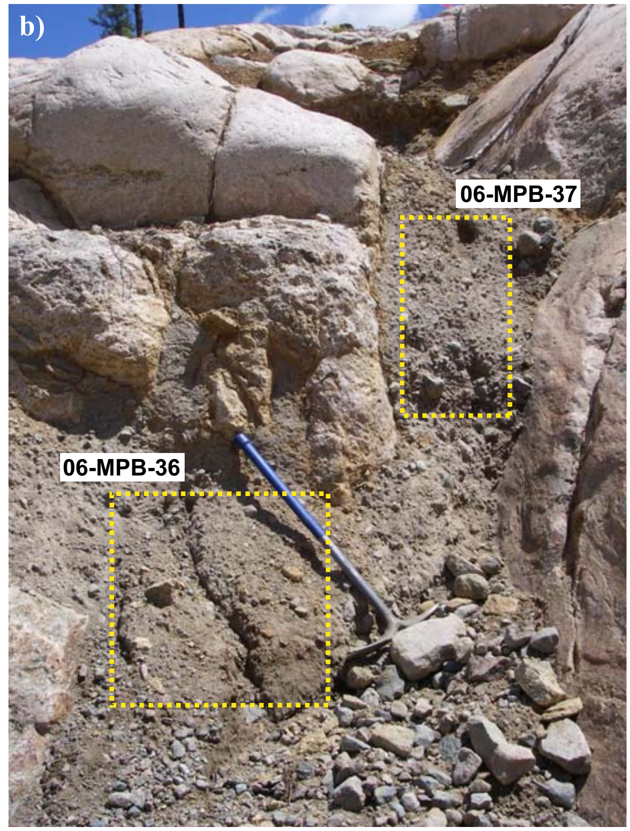


Figure 12. Site photographs showing the difference in colour between **(a)** the strongly oxidized, orange-brown till at site 09-MPB-026; and **(b)** the weakly oxidized, grey till at sites 09-MPB-36 and -37.

Source of high metal contents in till

Platinum, palladium, and gold

The maximum Pt and Pd values in the <0.063 mm fraction of till at the Broken Hammer site are some of the highest ever reported in the literature, and significantly higher than the 95th percentile values reported by Bajc and Hall (2000) for the North Range region (Table 4). 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 other PGM. Other PGM (e.g. merenskyite, melonite, michenerite, kotulskite: Table 1) have been reported in a sample (06-MPB-10, Fig. 2) of postglacial gossan developed on mineralized bedrock (Ames et al., 2007), and the mineralized zone (Watkinson et al., 2005; Péntek et al., 2008; Ames and Kjarsgaard, 2013).

Pt/(Pt+Pd) ratios for till samples (Table 2) range from 0.18 to 0.71, with the lowest values (<0.33) in metal-rich till proximal to mineralization, indicating these samples contain more Pd than Pt. The greater content of Pd reflects that reported Broken Hammer low-sulphide disseminated ore and massive sulphide veins (Péntek et al., 2008), and for other footwall deposits described by Farrow et al. (2005).

Elevated Pt and Pd values, as well as Cu, Ni, Bi, and Sb, in till sample 06-MPB-13, collected 25 m west the Big Boy vein, likely indicate the presence of a western extension of this vein system.

Gold values in till around the Broken Hammer occurrence are significantly greater than the 95th percentile values reported for the North Range region (Table 4). Elevated Au concentration (15–97 ppb) in the heavy mineral fraction of Pt- and Pd-rich till samples is not unexpected, as samples that contain abundant gold grains also contain abundant sperrylite (Table 2). The close association of Au with Pt and Pd in the till is supported by the observations of PGM and electrum in a sample of gossan from the main chalcopyrite vein (Ames et al., 2007). Péntek et al. (2008), however, report very weak correlations (r<0.30) between Au and Pt and Pd for the two types of mineralization at the Broken Hammer occurrence (disseminated and sharp-walled vein). Elevated gold concentrations in the <0.063 mm fraction of till likely reflect native gold in the occurrence (Tables 1 and 2).

Copper and nickel

Till down-ice of the main vein contains 100s to 1000s ppm Cu, which is significantly greater concentrations than the 95th percentile values for the North Range region (Table 4). These elevated values in till are usually accompanied by 10s to 1000s of chalcopyrite grains/10 kg (Table 2). Other Cu-bearing minerals that likely contributed to the Cu signature in till at Broken Hammer include bornite, covellite, wittichenite, emplectite, and malyshevite (Table 1). Only four till samples contain elevated Ni concentrations (101–344 ppm) greater than the 95th percentiles reported for the North Range region (Table 4). These samples are metal-rich till that was collected close to the main sharp-walled vein that contains millerite. The weaker Ni signature in the till, compared Cu, reflects the relatively low abundance of Ni-bearing minerals in the Broken Hammer sulphide veins as reported by Ames et al. (2007) and Péntek et al. (2008), and in general in other North Range footwall deposits studied by Farrow et al. (2005).

The Cu/(Cu+Ni) ratios for till samples are listed in Table 2. Ratios vary from 0.56 to 0.92, with highest values (>0.80) in the metal-rich till samples collected near mineralization, reflecting the strong Cu enrichment that is characteristic of the Broken Hammer and other footwall deposits in the Sudbury Camp (Péntek et al., 2008).

Other elements

Sn concentration is a useful vector in footwall systems in the North Range. For example, Broken Hammer (~7 ppm Sn), Wisner West (average 16 ppm Sn), and PM zone (6 ppm Sn) contain elevated concentrations relative to all North Range contact sulphide deposits(~1.8 ppm Sn), as well as compared to offset deposits (~3 ppm Sn) (Ames and Farrow, 2007; Ames et al., 2007; Kjarsgaard and Ames, 2010). Two till samples, 06-MPB-12, collected over the main sulphide vein, and 06-MPB-14, collected 35 m north of the main vein, contain elevated abundances of Sn (7 and 14 ppm, respectively), indicating that Sn may be a useful pathfinder element for this deposit type. Elevated Sn concentrations in till may reflect the presence of cassiterite.

The main Big Boy chalcopyrite-millerite vein at Broken Hammer contains telluride, bismuthide, and selenide minerals (Table 1). Till samples 06-MPB-011 and -012, collected over the main vein, contain elevated concentrations of Bi, Te, and Se, likely reflecting the presence of these telluride, bismuthide, and selenide minerals in the till. Thus, Bi, Te, and Se can be useful indicators of the presence of the Broken Hammer mineralization.

Elevated Ag concentrations (>95 ppb) in till samples 06-MPB-011, -012, -022, and -023, collected over or just down-ice of the main vein, likely reflect the presence of the abundant silver-bearing minerals such as hessite, electrum, naumannite, volynskite, and native silver in the main vein or gossan (Table 1). Elevated Cd values in till sample 06-MPB-011 may reflect the presence of sphalerite, which is a trace but ubiquitous mineral in the mineralization; although the low Zn values for this sample suggest that sphalerite is not the source. Other sources of Cd may include pyrite. Elevated Tl concentration in sample 06-MPB-013, collected over the gossan, may reflect the presence Tl in sphalerite or galena.

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. This low abundance in till may indicate that the elevated Pt contents in the till are derived from non-As bearing PGM as well as from sperrylite. Based on the data presented here, As in the till matrix does not indicate the presence of Broken Hammer mineralization.

Indicator and pathfinder elements

The term "indicator element" is used here to refer to an element that is an economically valuable component of the ore being sought and may be used to detect an orebody (Rose et al., 1979). The results reported here indicate that Pd, Pt, Cu, Ni, Au, and Ag are the optimal indicator elements for the Broken Hammer occurrence. The term "pathfinder element" is used here to refer to non-ore elements associated with the orebody that may be used to detect the orebody (Rose et al., 1979). Pathfinder elements in till overlying and down-ice of the Broken Hammer occurrence include Cd, Sb, Bi, Se, Te, Tl, and Sn.

Comparison of till geochemistry to indicator mineral counts

Platinum and Pd concentrations in <0.063 mm fraction of till in this study were used to predict which samples should contain visible sperrylite grains in the heavy mineral fraction. Visible sperrylite grains were recovered from eight till samples; however, elevated Pd and Pt values were reported to occur in more than these eight samples. As a result, the <0.25 mm fractions of all till heavy mineral concentrates were repanned and up to 50 sperrylite grains per sample (15–75 µm) were found in an additional 11 samples: 06-MPB-008, -009, -022, -024, -025, -027, -031, -032, -035 to -037 (Table 2).

Metal-rich till (Pd, Pt, Au, Cu, Ni, and Ag) was found at least 125 m down-ice (sample 06-MPB034) of the main vein at the Broken Hammer occurrence. In contrast, sperrylite, gold, and chalcopyrite grains in till were found at least 600 m down-ice (sample 06-MPB-31) of the main vein, indicating that till geochemical signatures cannot be detected as far down-ice as indicator minerals for this occurrence on the North Range. These two observations about anomalous metal concentrations and indicator mineral counts demonstrate the importance of determining till geochemistry in combination with indicator mineral counts for Pt and Pd exploration.

Table 5. Comparison, at regional and deposit scales, of the geochemical signature in the <0.063 mm fraction of till at the Broken Hammer occurrence with other magmatic Ni-Cu-PGE deposits in glaciated terrain of Canada. Percentile values for the Broken Hammer site were calculated using data from this study (n=38) plus data for till samples collected within a 7 km radius of Broken Hammer (n=35) and reported by Bajc and Hall (2000).

Location	Values	Pt ppb	Pd ppb	Au ppb	Ni ppm	Cu ppm	No. of samples	Source of data
Broken Hammer, Sudbury, ON	95th percentile	37.0	96.0	29	109	778	73	this study
Barnet Property, Sudbury, ON	highest value	2.8	2.8	11	12	158	9	Bajc and Hall (2000)
Parkin Offset, Sudbury, ON	95th percentile	5.7	11.8	NR	NR	NR	50	Bajc and Hall (2000)
Strathcona Embayment, Sudbury	95th percentile	3.0	4.7	NR	189	671	52	Bajc and Hall (2000)
Thompson Deposit, Thompson Ni Belt, MB	95th percentile	10.3	97.9	8	3760	215	14	McClenaghan et al. (2009)
Pipe Deposit, Thompson Ni Belt, MB	95th percentile	13.1	19.8	9	1759	123	15	McClenaghan et al. (2009)
Powerhouse Zone,Lac des Iles, ON	95th percentile	9.1	61.3	8	185	109	20	Searcy (2001)
Baker Zone, Lac des Iles, ON	95th percentile	4.3	12.8	4	229	94	45	Searcy (2001)
Tulameen, BC	mean	52.8	8.9	8	NR	NR	17	Cook and Fletcher (1993)
Rottenstone Lake, SK	highest value	6.0	4.0	63	200	207	17	Coker et al. (1990)

NR= not reported

Sites distal to the Broken Hammer occurrence

Elevated Pt and Cu concentrations in till sample 06-MPB-006 on the Wisner West property, as well as a significant number of visible chalcopyrite grains, reflect the known mineralization at this site. The Onaping Formation is host to numerous hydrothermal Zn-Cu-Pb occurrences and deposits (Ames et al., 2006a). The highest Mo, Zn, Pb, As, and Cd contents in this study are in till samples 06-MPB-008 and 06-MPB-039, which overlie the Onaping Formation. These elevated values may reflect the presence of VMS mineralization (Ames et al., 2005; 2008).

Till weathering

Bajc and Hall (2000) reported that the highly oxidized till (B-horizon soil developed on till) around Ni-Cu-PGE deposits in the Sudbury region was depleted in metals compared to the C-horizon due to hydromorphic dispersion of metals held in sulphides as well as the translocation of clay-sized particles downward within a soil profile (Table 4). For this reason, the authors recommended that till samples should be collected from the least weathered material, ideally at a depth of at least 1 m. In this study, however, till at some sites was <1 m thick resting on bedrock, and as a result, highly oxidized B-horizon soil developed on till was the only material available to sample. Till samples affected by varying degrees of oxidation (Table 2) were sampled from mineralized and background areas. The range of strongly to weakly oxidized samples (Fig. 12) proximal to the deposit (<200 m down-ice) contain high concentrations of Pt, Pd, and Cu, as well as sperrylite. While unoxidized to weakly oxidized till is the ideal sample medium, moderate to strongly oxidized till is also a useful sample medium in this area.

Comparison of till geochemical signatures to other magmatic Ni-Cu-PGE deposits in the Sudbury Basin

The regional till survey (Table 4) of the Sudbury North Range by Bajc and Hall (2000) provides the regional context in which to interpret the Broken Hammer till geochemical data. The Broken Hammer till values greatly exceed the regional till 95th percentile values for the following indicator and pathfinder elements: Cu, Ni, Pt, Pd, Au, Sb, Bi, Se, and Te. Bajc and Hall (2000) reported a similar suite of indicator and pathfinder elements for Sudbury-type Ni-Cu-PGE mineralization that included Au, Cr, Co, Ag, Pb, As, Se, Sb, Te, Bi, Mn, and Fe.

In particular, their study included detailed till sampling around a footwall occurrence on the Barnet property in the Strathcona embayment, 30 km west-southwest of the Broken Hammer occurrence. On this property, narrower Cu-rich veins occur within footwall gneiss and Sudbury Breccia with an average grade of 0.6% Ni and 4.0% Cu, and combined average PGE values of <1 ppm, which in places exceeds 10 ppm (Coker et al., 1991). Bajc and Hall (2000) demonstrated that till proximal to this footwall deposit contains elevated Cu, Au, and Pd (Table 5); however, the highest reported values are much lower than the 95th percentile values reported for Broken Hammer.

Bajc and Hall (2000) also conducted closely spaced till sampling around contact Ni-Cu-Co deposits (low Cu:Ni ratios (<1) and low precious metal contents) at the Victor and Nickel Rim (15 km southeast), Whistle (7 km east), and Strathcona Embayments (20 km southwest) deposits (Table 5) close to the basal contact of the Sudbury Igneous complex. Till proximal to the economic Strathcona Embayments deposits contain anomalous levels of Cu and Ni, and moderately elevated contents of Pt and Pd. Offset deposits (Parkin, Ministic, Foy) (higher Cu:Ni ratios (~1) and enriched precious metal contents) were also studied by Hall and Bajc (2000). Till around the Parkin offset (Table 5), which is one of the mineralized offset dykes studied by Bajc and Hall (2000), has moderately elevated Pt and Pd values compared to this study. In general, till sampled in case studies by Bajc and Hall (2000) contain much less Pd, Pt, Cu, and Ni than till around the Broken Hammer occurrence.

Till geochemistry analyses of this study detected dispersal of pathfinder elements at least 125 m down-ice from the Broken Hammer occurrence. Bajc and Hall (2000) reported that dispersal trains around Pt- and Pd-rich footwall occurrences/showings of discontinuous veins, veinlets, and sometimes disseminations tend to be short (less than a few 100 m). In contrast, those derived from Ni and Cu massive orebodies are longer, commonly ranging between 500 and 2000 m in length.

Comparison of till geochemical signatures to other magmatic Ni-Cu-PGE deposits in Canada

The 95th percentiles for the Broken Hammer site were calculated using data from this study (n=38) plus data for till samples within a 7 km radius of Broken Hammer (n=35) reported by Bajc and Hall (2000). Table 5 compares these data to other deposit-scale till geochemical studies of Ni-Cu-PGE deposits in Canada. Note that the analytical methods in each study were not all the same. Platinum content of the Broken Hammer till is among the highest, second only to the Tulameen Pt deposit in British Columbia (Cook and Fletcher, 1992). Palladium values for Broken Hammer till are similar to those reported for the Thompson Ni deposit, Manitoba (McClenaghan et al., 2011) and the Powerhouse Zone at Lac des Isles, Ontario (Searcy, 2001). Gold values in till at Broken Hammer are among the highest reported for Ni-Cu-PGE deposits (Table 5). Nickel values in till in this study are low compared to other deposits, which is not unexpected as the Ni content in the occurrence is low. As expected for till down-ice of a massive chalcopyrite vein hosting PGEs, Cu values in till at Broken Hammer are the highest reported (Table 5).

CONCLUSIONS

Glacial erosion indicators (striations and sculpted bedrock surfaces) are readily apparent on bedrock outcrops in the study area and confirm Bajc's (1997a-c) observations that ice flowed southward across the Broken Hammer region and the North Range of the Sudbury Basin. Till sample sites were selected to characterize the mineralogical and geochemical signatures (<0.063 mm fraction) of mineralization at varying distances down-ice. Within 10 m of the ore zone, till contains 1000s of sperrylite grains, 100s of chalcopyrite and gold grains, and highly anomalous values of Pt, Pd, Au, Cu, Ni, Se, Te, Ag, Cd, Bi, and Sn. Most Pt/(Pt+Pd) ratios for till are low (0.2–0.3), indicating close proximity to Pd-rich mineralization; most Cu/(Cu+Ni) ratios are high (>0.8), indicating Cu-rich mineralization.

Between 10 and 50 m down-ice, till contains 10s of sperrylite, chalcopyrite, and gold grains, and moderately anomalous values of Pt, Pd, Au, Cu, and Sn. Similar to proximal metal-rich till, most Pt/(Pt+Pd) ratios are low (0.2–0.3) and most Cu/(Cu+Ni) ratios are high (>0.8).

Between 50 and 250 m down-ice, till contains a few visible sperrylite grains and 10s of gold grains, and has moderate to weakly anomalous values of Pt, Pd, and Cu; most Pt/(Pt+Pd) ratios are significantly higher (0.5–0.66) and most Cu/(Cu+Ni) ratios are lower (0.5–0.7). Beyond 250 m down-ice, the spacing of the till samples was not sufficient to determine the distance down ice-that mineralogical and geochemical signatures from the Broken Hammer occurrence may or may not be detected. However, one till sample collected 600 m down-ice did contain sperrylite grains.

Based on the geochemical patterns reported here for till, the indicator elements for this Cu-(Ni-)-PGE footwall occurrence include Pt, Pd, Cu, Ni, Au, and Ag. Pathfinder elements include Sb, Bi, Se, Te, Cd, Tl, and Sn. The suite of indicator and pathfinder elements can be determined using a combination of aqua regia/ICP-MS, fire assay/ICP-MS, and borate fusion/nitric acid ICP-MS techniques. Low Pt/(Pt+Pd) ratios (<0.3) and high Cu/(Cu+Ni) ratios (>0.8) are also strong indicators of proximity to mineralization. These results are useful guides for exploring for footwall-style mineralization in the Sudbury region, as well as Ni-Cu-PGE mineralization elsewhere in glaciated terrain.

Historically, till geochemistry has not been used for Cu-Ni-PGE exploration in the Sudbury region. This study, combined with that of Bajc and Hall (2000) and Coker et al. (1990, 1991), demonstrates that till geochemistry combined with indicator mineral methods is 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, oxidized till is also worthwhile sampling if it is the only medium available.

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APPENDIX A. Till sample location information

Appendix A.2. Photos of till sample sites.

Till sample site 06-MPB-001, on logging road 6 km north of the deposit: **a)** a view of the bouldery nature of the till at the surface; **b)** samples collected at a road cut; **c)** close-up of the sample site.

Till sample site 06-MPB-002, on road 6 km north of the deposit: **a)** over view of the sample site; **b)** close-up of the sample site showing the loose sandy nature of the material at this site.

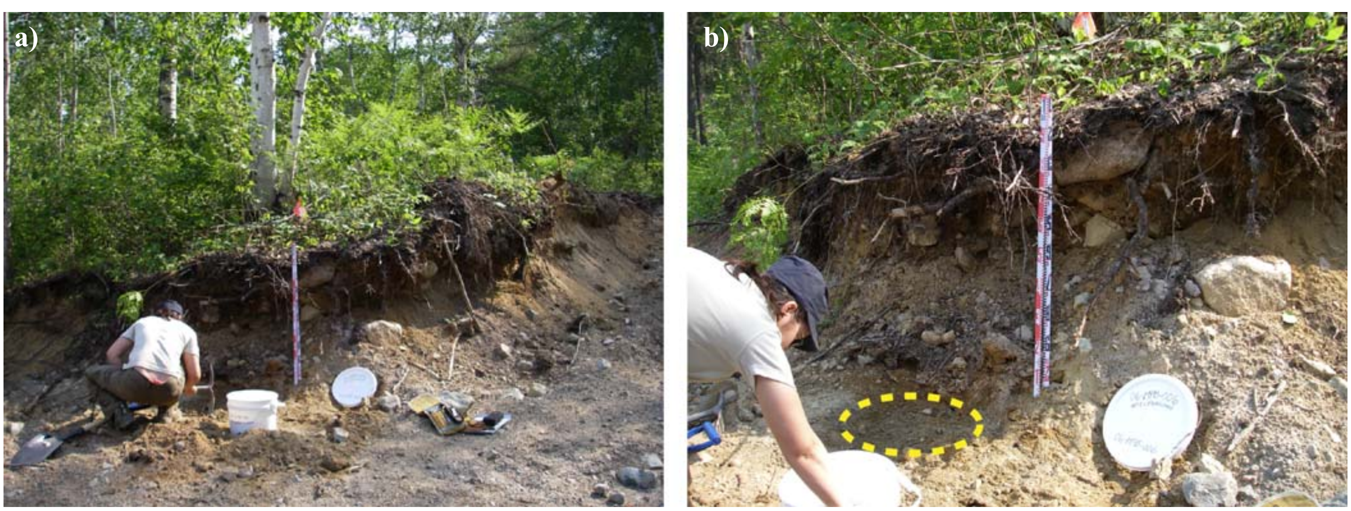
Appendix A.2 continued.

Till sample site 06-MPB-003, in road-cut on forest access road 6 km north of the deposit: **a)** an overview of the sample site; **b)** close-up of the sample site prior to sampling showing the loose sandy nature of material at the site; **c)** close-up of the sample site.

Appendix A.2 continued.

Till sample site 06-MPB-004, in road-cut on forest access road 4 km west of the Broken Hammer occurrence: **a)** view of the sample site location relative to bedrock outcrop; **b)** close-up of the site showing the loose sandy nature of till that was sampled.

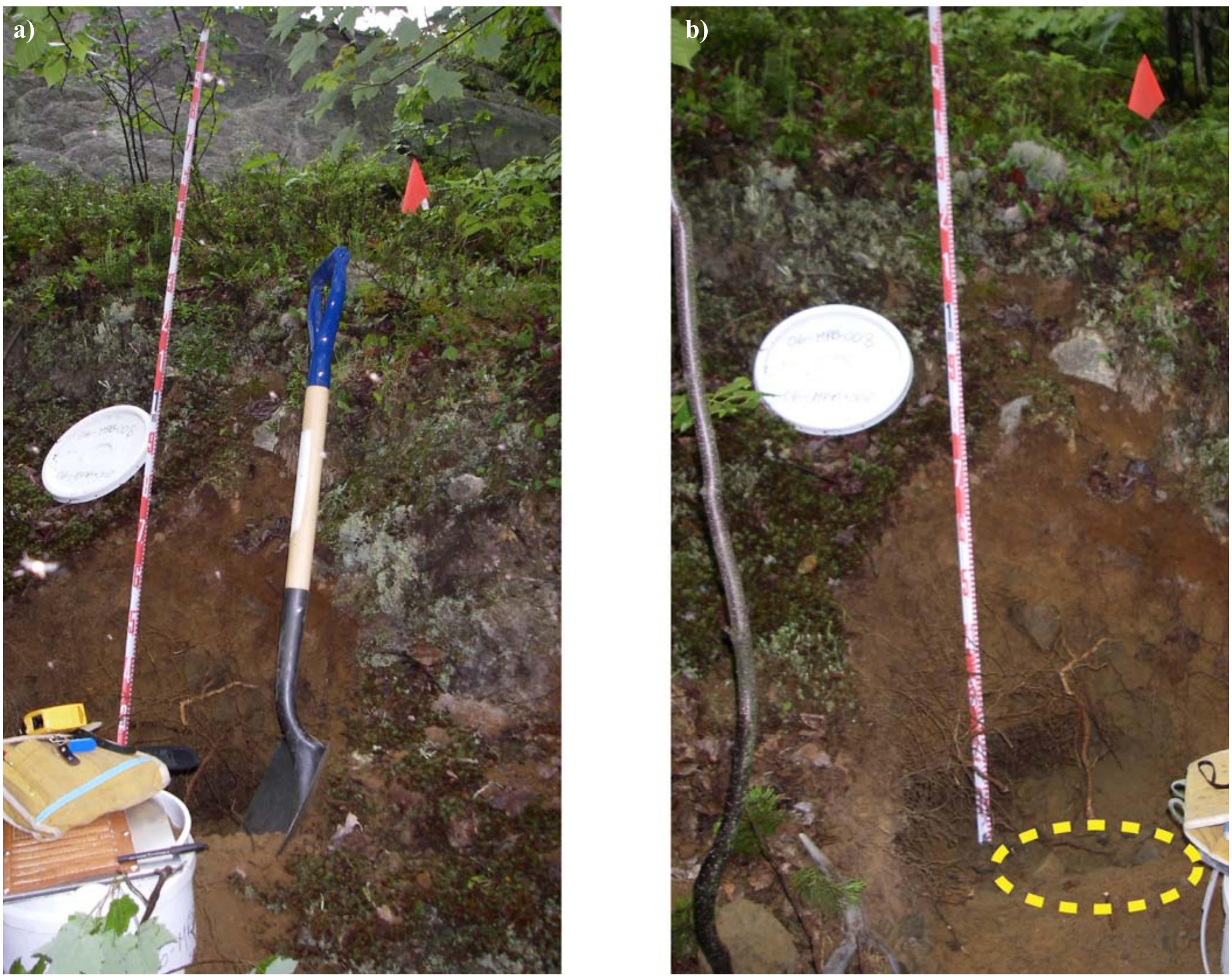
Till sample site 06-MPB-005, in a road-cut at a diamond drillhole site, 3 km west-southwest of the Broken Hammer occurrence: **a)** view of the sample site section; **b)** close-up of the site showing the stoney sandy nature of till that was sampled.



Till sample site 06-MPB-006, in road-cut on a drill-site access trail 3 km southwest of the Broken Hammer occurrence: **a)** view of the sample site; **b)** close-up of the site showing the stoney nature of the till. The sample site is indicated by a yellow dashed line.

Appendix A.2 continued.

Till sample site 06-MPB-007, in road-cut on a forest access road 3.5 km southwest of the Broken Hammer occurrence: **a)** overview of the sample site; **b)** close-up of the site. The sample site is indicated by a yellow dashed line.



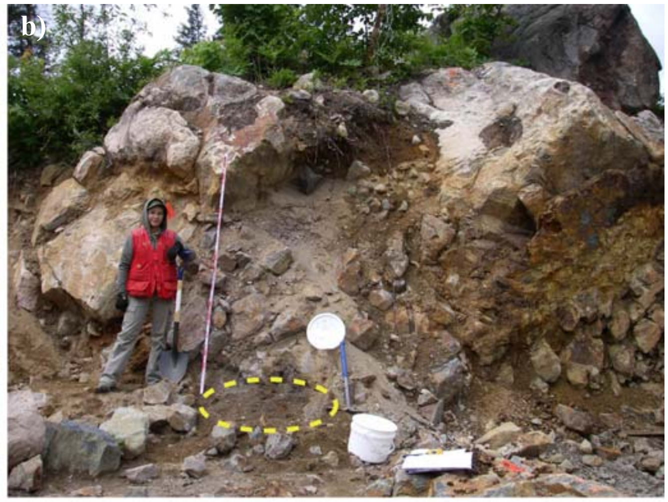
Till sample site 06-MPB-008, in road-cut on a forest access road 8 km sooth of the Broken Hammer occurrence: **a)** view of the sample site; **b)** view of the site showing the highly oxidized nature of the till that was sampled. The sample site is indicated by a yellow dashed line.

Appendix A.2 continued.

Till sample site 06-MPB-009, adjacent to the Big Boy vein at the Broken Hammer occurrence: **a)** overview of sample site adjacent to a bedrock outcrop; **b)** close-up of the stoney sandy till that was sampled. Sample site is indicated by a yellow dashed line.

Gossan sample site 06-MPB-010 at the Broken Hammer occurrence: **a)** collecting a sample of post-glacial gossan that has formed on a chalcopyrite vein; **b)** close-up of the gossan; **c)** honeycomb texture of the gossan.

Appendix A.2 continued.



Till sample site 06-MPB-011, 2 m south of the Big Boy chalcopyrite vein at the Broken Hammer occurrence: **a)** overview of the site just south of sample site 06-MPB-010; **b)** till sampled at the base of the section on the up-ice side of a bedrock knob; **c)** close-up view of the sample site.

Appendix A.2 continued.

Till sample site 06-MPB-012, 1 m of the Big Boy chalcopyrite vein at the Broken Hammer occurrence: **a)** overview of site just west of sample site 06-MPB-010; **b)** till sampled at the base of the section on the up-ice side of a bedrock knob; **c)** close-up view of the sample site.

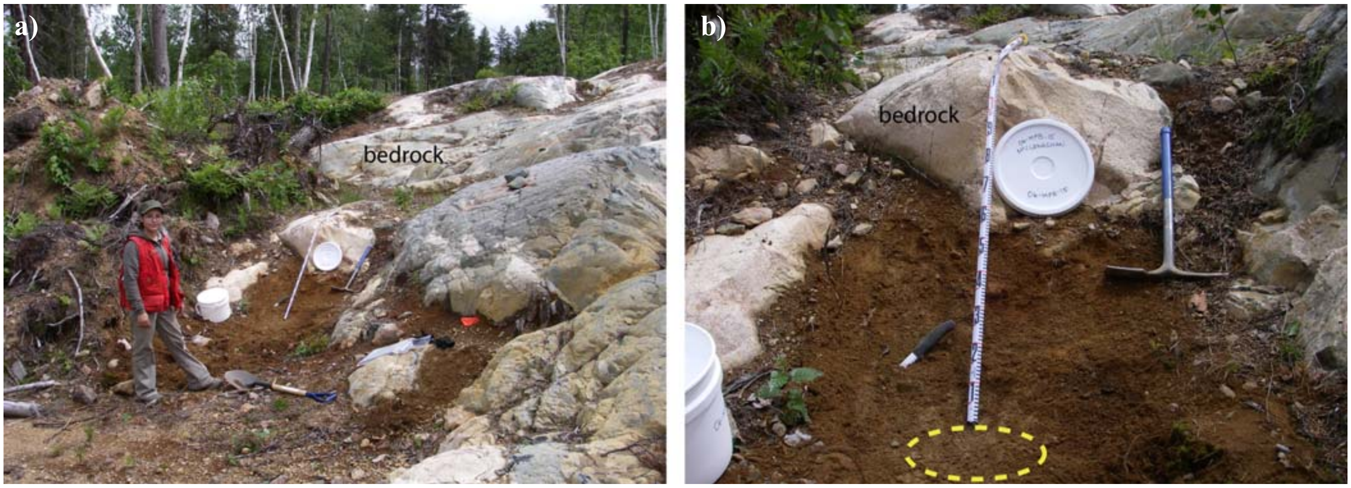
Appendix A.2 continued.

Till sample site 06-MPB-013, 25 m west of the Big Boy chalcopyrite vein at the Broken Hammer occurrence: **a)** overview of the sample site, which is in the wall of a trench; **b)** till was sampled at the base of a 2 m section of exposed till that is sitting on bedrock **c)** close-up of the sample site, which is highlighted by a yellow dashed line.

Appendix A.2 continued.

Till sample site 06-MPB-014, 45 m north of the Big Boy chalcopyrite vein at the Broken Hammer occurrence: **a and b)** over-view of the sample site, which is in the wall of a shallow trench; **c)** till was sampled at the base of shallow till section, overlying bedrock (sample site highlighted by a yellow dashed line).

Appendix A.2 continued.



Till sample site 06-MPB-015, 60 m north of the Big Boy chalcopyrite vein at the Broken Hammer occurrence: **a)** overview of the sample site, which is in the wall of a shallow trench; **b)** till was sampled at the base of the shallow till section overlying bedrock (sample site location is highlighted by a yellow dashed line).

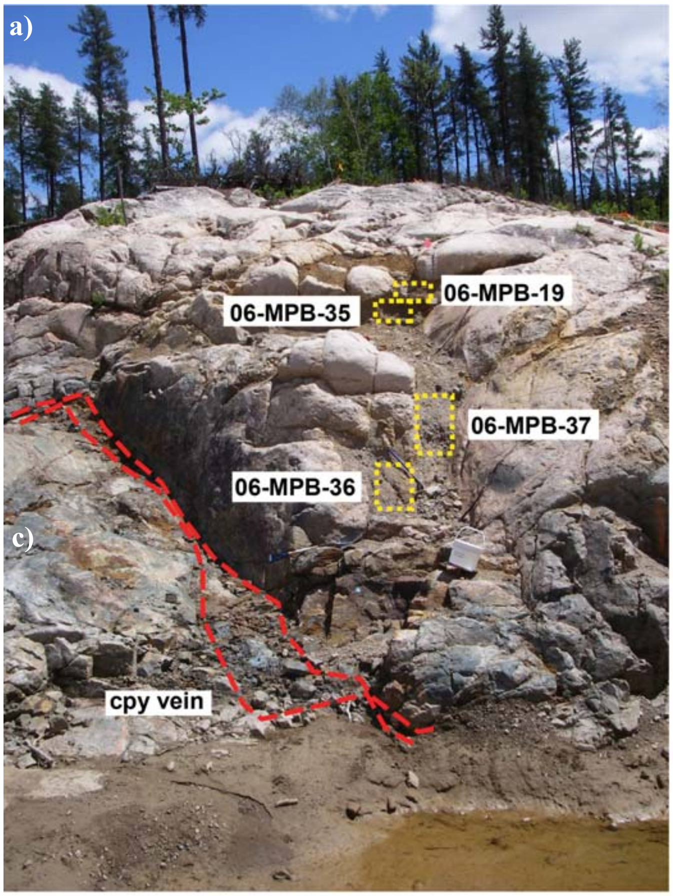
Till sample site 06-MPB-016, 80 m northeast of the Big Boy chalcopyrite vein at the Broken Hammer occurrence: **a)** overview of the sample site in the wall of a shallow trench; **b)** till was sampled at the base of a shallow till section that overlies bedrock (sample site location is highlighted by a yellow dashed line).

Till sample site 06-MPB-017, 150 m northeast of the Big Boy chalcopyrite vein at the Broken Hammer occurrence: **a)** overview of the sample site in a depression on a bedrock surface; **b)** close-up view of the till sample site overlying bedrock (sample site location is highlighted by a yellow dashed line).

Appendix A.2 continued.

Till sample site 06-MPB-018, 2 m north of the Big Boy chalcopyrite vein at the Broken Hammer occurrence: **a)** overview looking south showing of the sample site in the main trench showing and a chalcopyrite vein and other sample sites; **b** and **c)** close-up view of the till sample site (sample location is highlighted by a yellow dashed line).

Appendix A.2 continued.



Till sample sites 06-MPB-019 and 06-MPB-035, 2 m south of the Big Boy chalcopyrite (cpy) vein (margins are indicated by red dashed line): **a)** overview of the sample sites just south of the vein (note the white cooler for scale); **b and c)** close-up views of the till sample sites with the locations highlighted by yellow dashed lines.

Appendix A.2 continued.

Till sample site 06-MPB-020, 250 m northeast of the Big Boy chalcopyrite vein at the Broken Hammer occurrence: **a)** overview of the sample site in an exposed section on a bush trail;
b) close-up of the stoney sandy till that was sampled. The sample site is indicated by a yellow dashed line.

Appendix A.2 continued.

Till sample site 06-MPB-021, 125 m northeast of the Big Boy chalcopyrite vein at the Broken Hammer occurrence: **a and b)** overview of the sample site overlying exposed bedrock in a trench; **c)** close-up of the stoney sandy till that was sampled. Sample site is indicated by a yellow dashed line.

Till sample site 06-MPB-022, 7 m east of the Big Boy chalcopyrite vein at the Broken Hammer occurrence: **a)** overview of the sample site, which overlies bedrock that has been exposed in a trench; **b)** stoney sandy till that was sampled. Sample site is indicated by a yellow dashed line.

Appendix A.2 continued.

Till sample site 06-MPB-023, 2 m south of the Big Boy chalcopyrite vein at the Broken Hammer occurrence: **a and b)** overview of the sample site, which overlies bedrock exposed in trench; **c and d)** stoney sandy till that was sampled. Sample site is indicated by a yellow dashed line.

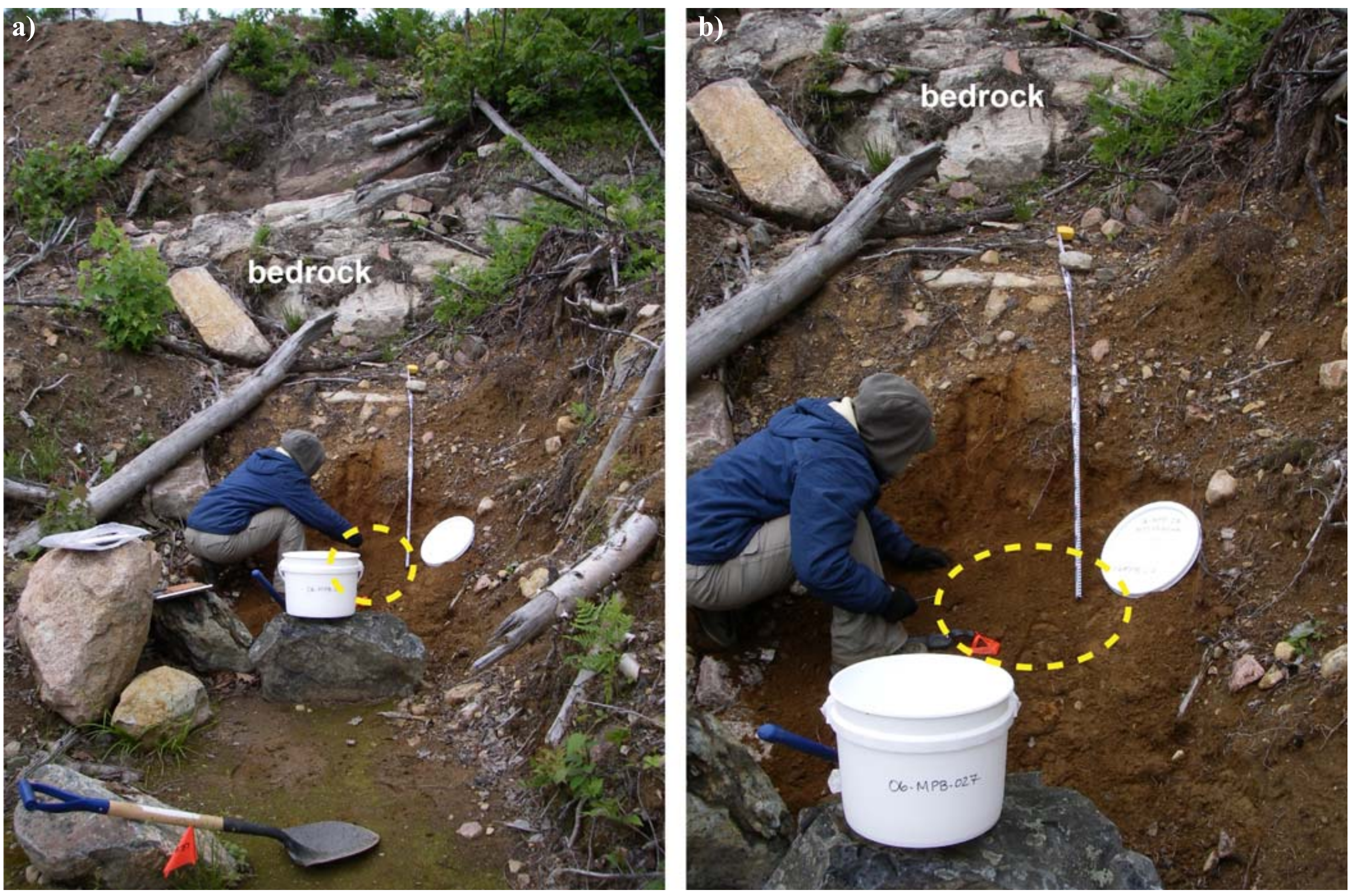
Appendix A.2 continued.

Till sample site 06-MPB-024, 20 m south of the Big Boy chalcopyrite vein at the Broken Hammer occurrence: **a)** overview of the sample site showing the very thin till that overlies bedrock; **b)** sampled sandy till. Sample site is indicated by a yellow dashed line.

Till sample site 06-MPB-025, 25 m south of the Big Boy chalcopyrite vein at the Broken Hammer occurrence: **a and b)** over-view of the exposed sample site in clearing where sandy till was sampled. Sample site is indicated by a yellow dashed line.

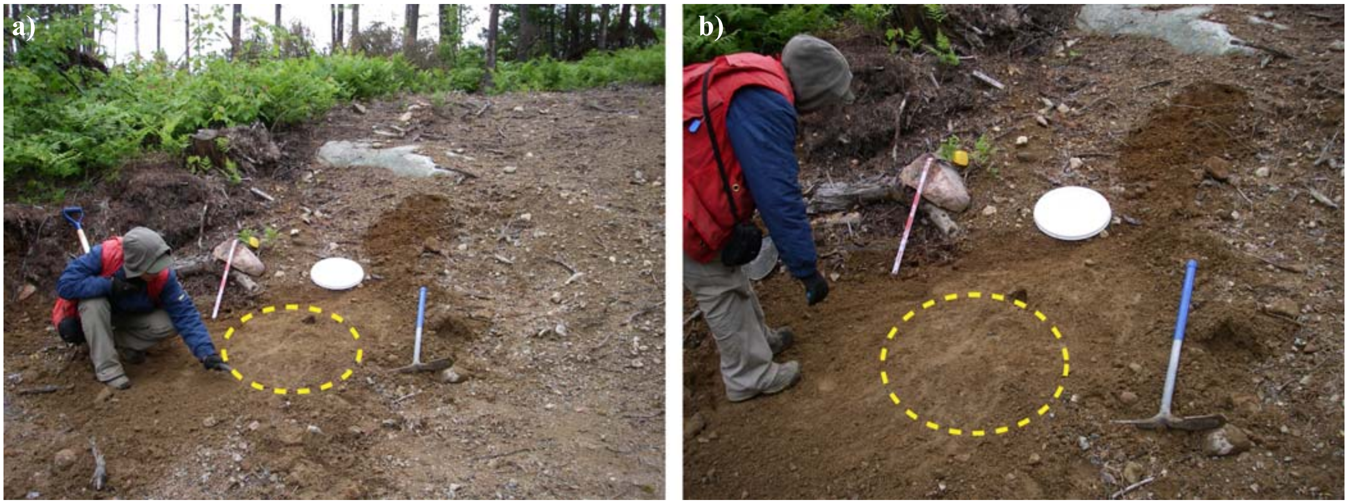
Appendix A.2 continued.

Till sample site 06-MPB-026, 30 m south of the Big Boy chalcopyrite vein at the Broken Hammer occurrence: **a)** overview of the sample site, which overlies bedrock in a trench; **b)** sandy till that was sampled. Sample site is indicated by a yellow dashed line.



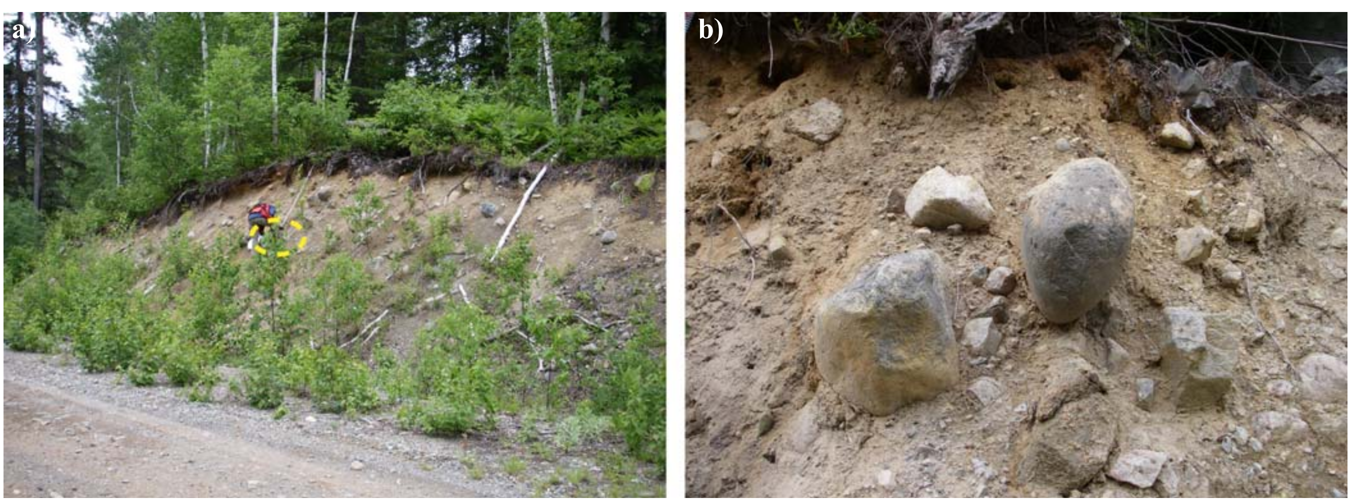
Till sample site 06-MPB-027, 7 m south of the Big Boy chalcopyrite vein at the Broken Hammer occurrence: **a)** overview of the sample site, which is in trench adjacent to exposed bedrock; **b)** highly oxidized sandy till that was sampled. Sample site is indicated by a yellow dashed line.

Appendix A.2 continued.



Till sample site 06-MPB-028, 9 m south of the Big Boy chalcopyrite vein at the Broken Hammer occurrence: **a)** overview of the sample site in clearing, adjacent to exposed bedrock; **b)** sandy till that was sampled. Sample site is indicated by a yellow dashed line.

Till sample site 06-MPB-029, 100 m south of the Big Boy chalcopyrite vein at the Broken Hammer occurrence. Sample site is indicated by a yellow dashed line.



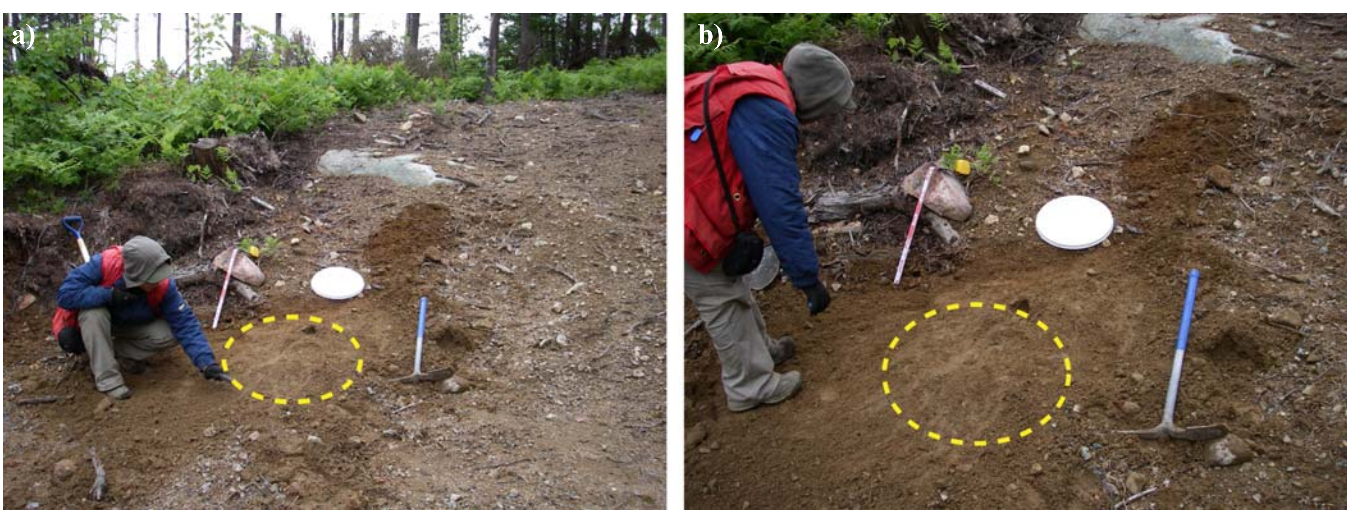
Till sample site 06-MPB-030, 1500 m southeast of the Broken Hammer occurrence: **a)** overview of the sample site in a road-cut on south side of the main access road; **b)** section of stoney sandy till. Sample site is indicated by a yellow dashed line.

Appendix A.2 continued.

Till sample site 06-MPB-031, 600 m south of the Broken Hammer occurrence: **a)** overview of the sample site exposed in a roadside trench; **b)** cleared section with the blade of a shovel resting on the bedrock; **c)** close-up of the sandy till that was sampled. Sample site is indicated by a yellow dashed line.

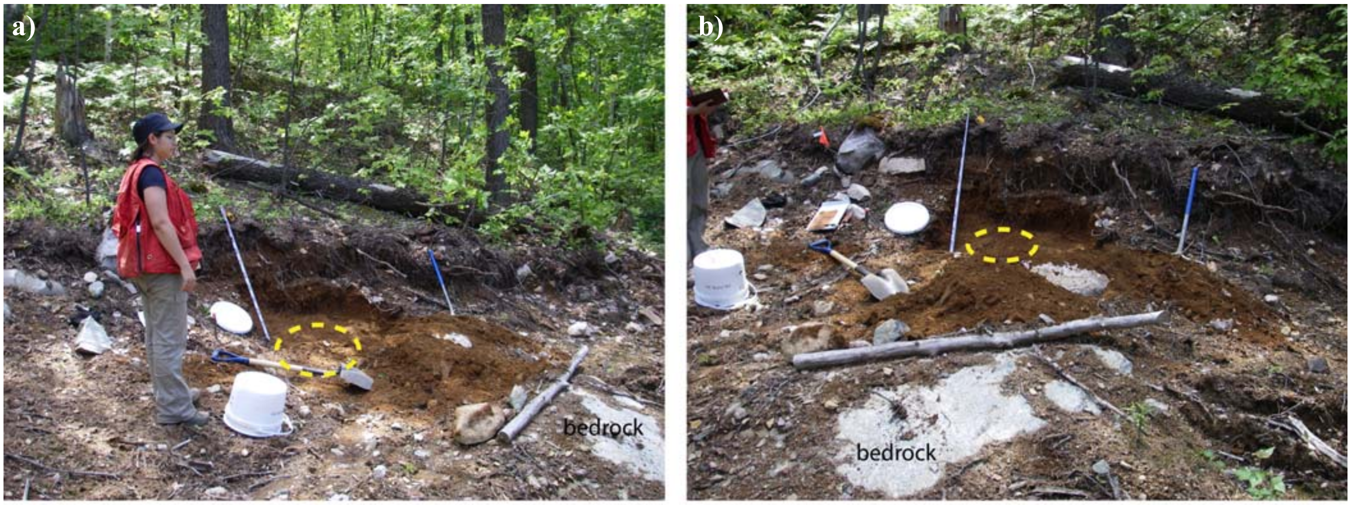
Appendix A.2 continued.

Till sample site 06-MPB-032, 200 m south of the Broken Hammer occurrence: **a)** overview of the sample site on the west side of the main access road; **b)** stoney sandy till that was sampled in a section exposed on west side of the road; **c)** close-up of the sample site. The sample site indicated is by a yellow dashed line.



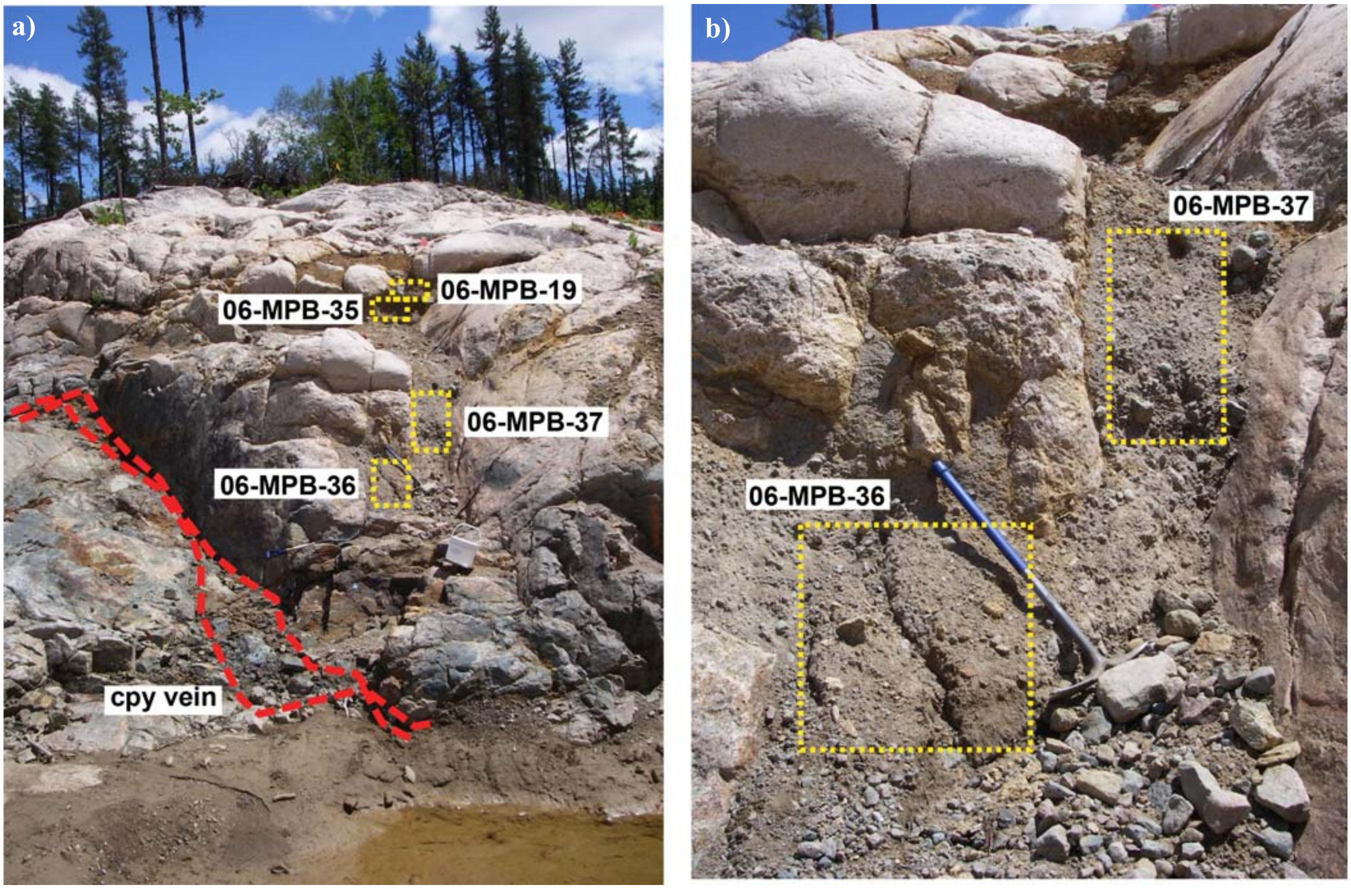
Till sample site 06-MPB-033, 170 m south of the Big Boy chalcopyrite vein: **a)** overview of the sample site adjacent to bedrock outcrop on the side of a bush trail; **b)** close-up of sandy till that was sampled. Sample site is indicated by a yellow dashed line.

Appendix A.2 continued.



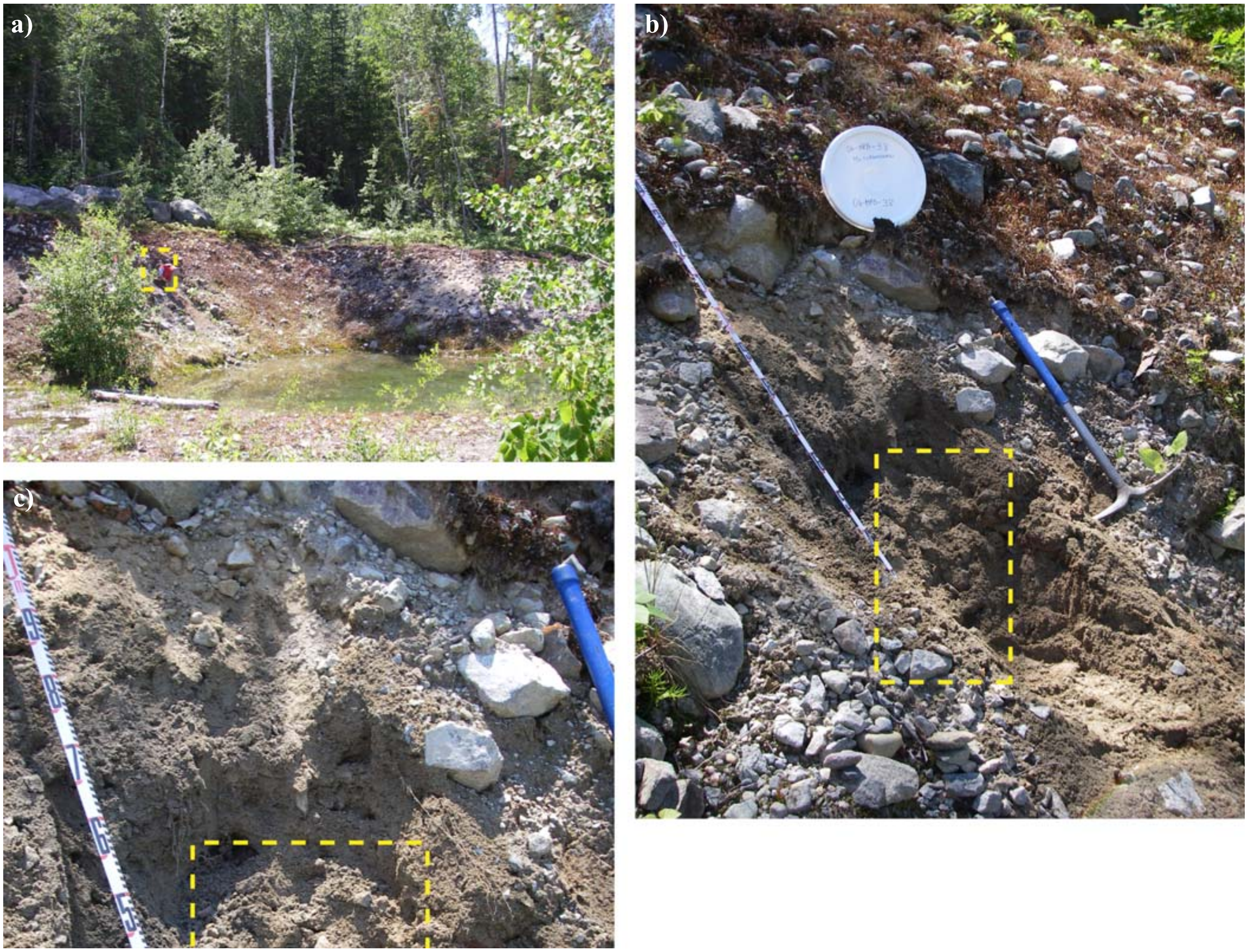
Till sample site 06-MPB-034, 170 m south of the Big Boy chalcopyrite vein: **a and b)** overview of the sample site adjacent to a bedrock outcrop on the side of a bush trail; **c)** close-up of sandy till that was sampled. Sample site is indicated by a yellow dashed line.

Appendix A.2 continued.



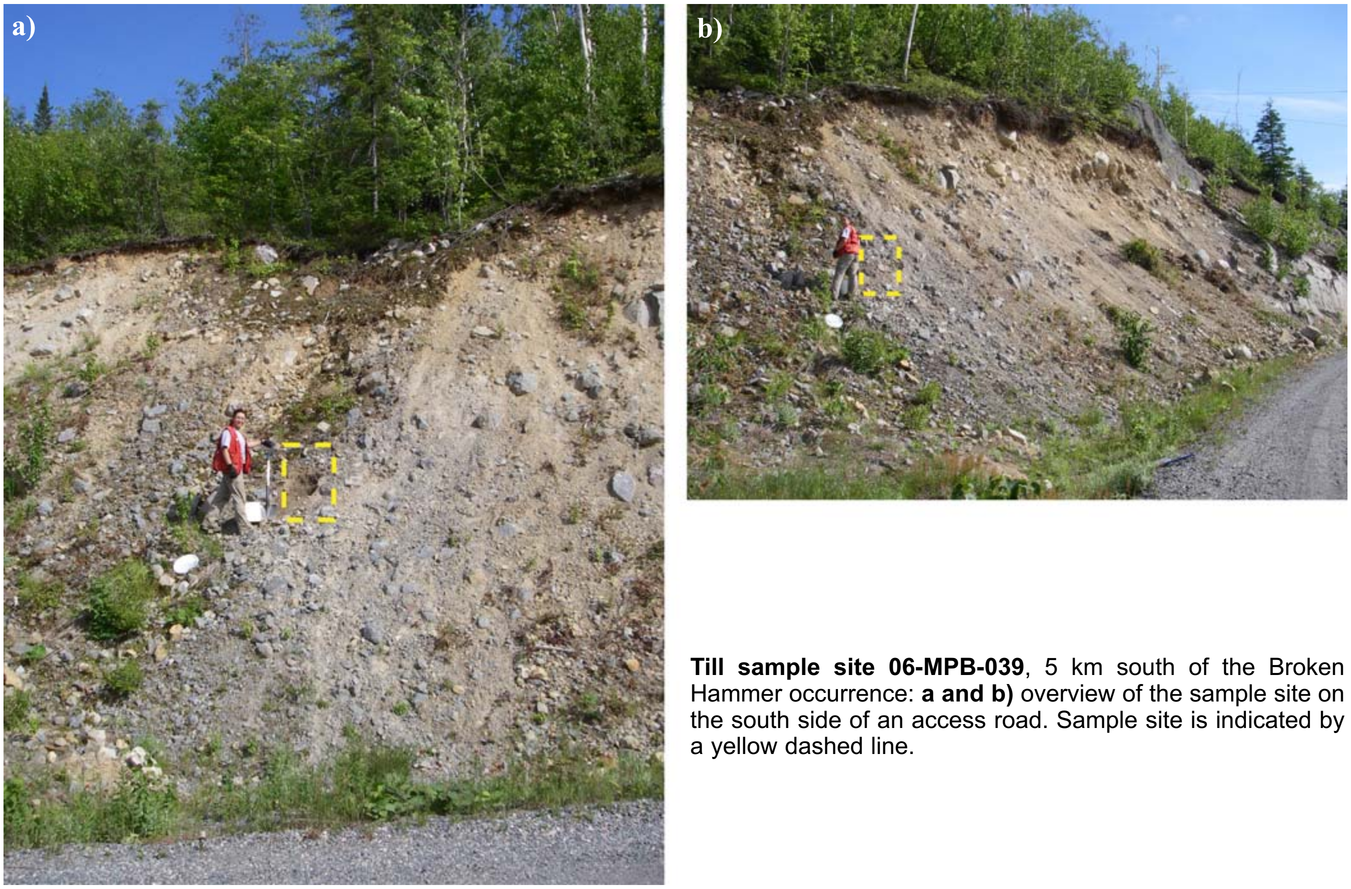
Till sample sites 06-MPB-036 and 06-MPB-037, 1 m south of the Big Boy chalcopyrite (cpy) vein (margins are indicated by red dashed line): **a)** overview of the sample sites just south of the vein (note the white cooler for scale); **b)** close-up of sandy till that was sampled. Sample sites are indicated by yellow dashed lines.

Appendix A.2 continued.



Till sample site 06-MPB-038 in a borrow pit, 1500 m south of the Broken Hammer occurrence: **a)** overview of the sample site in the south wall of a pit; **b and c)** close-up of sandy till that was sampled. Sample site is indicated by a yellow dashed line.

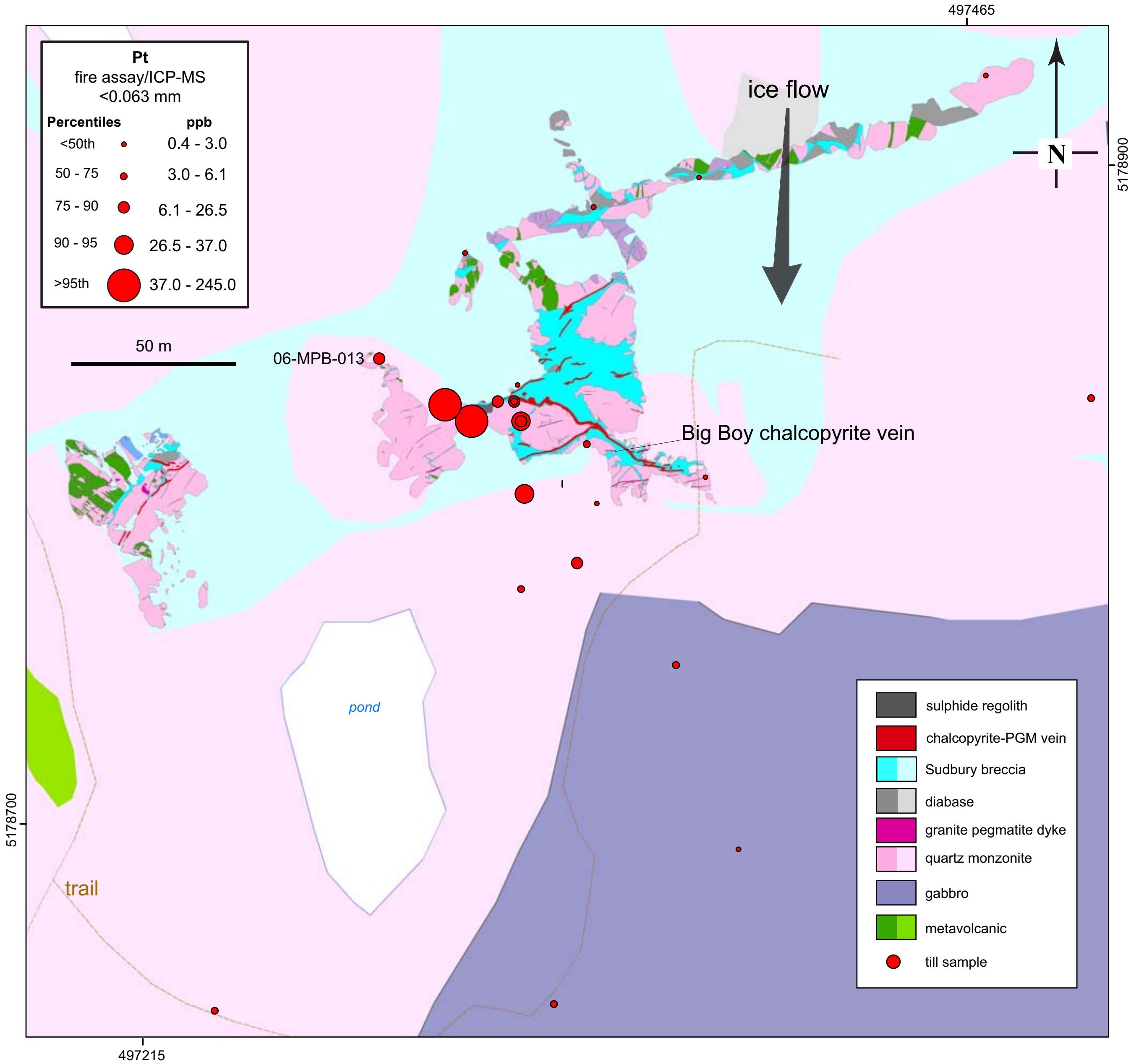
Appendix A.2 continued.



Till sample site 06-MPB-039, 5 km south of the Broken Hammer occurrence: **a and b)** overview of the sample site on the south side of an access road. Sample site is indicated by a yellow dashed line.

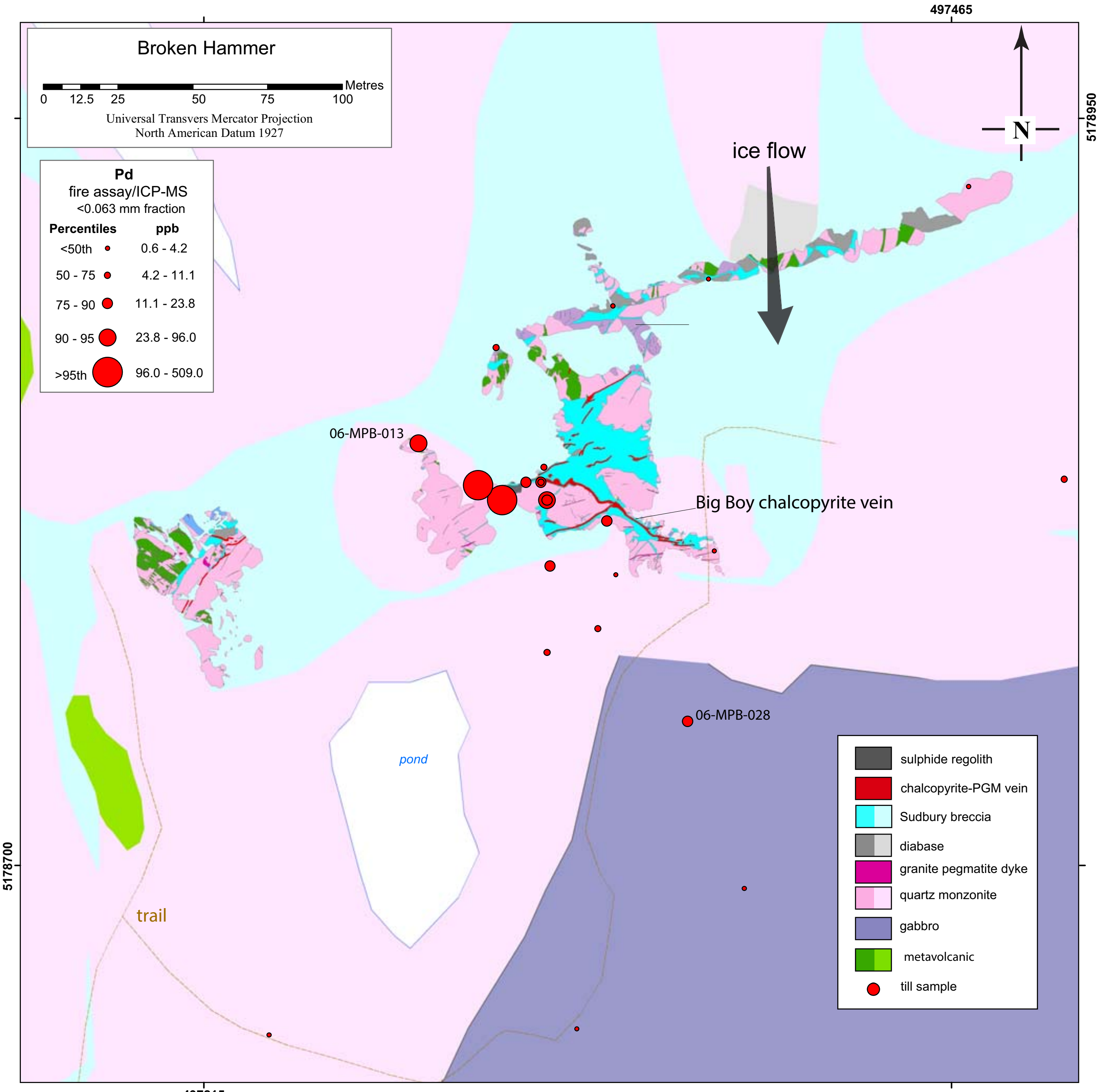
APPENDIX C.

Deposit-scale proportional dot maps of element abundance in the <0.063 mm fraction of till proximal to the Broken Hammer occurrence



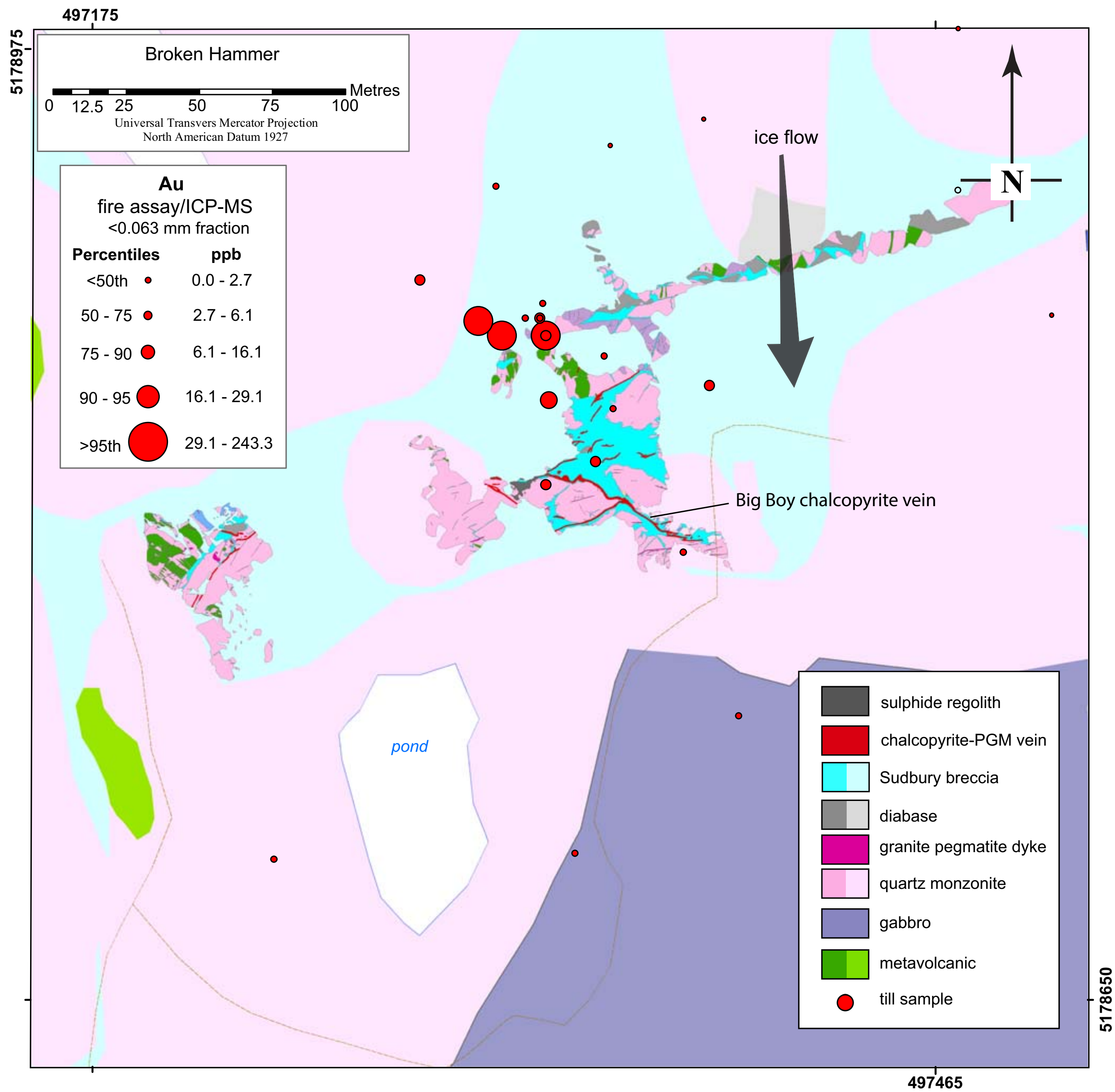
Map 1. Abundance of platinum in the <0.063 mm fraction of till proximal to the Broken Hammer occurrence (detailed bedrock geology from Peterson et al., 2004; regional bedrock geology from Ames et al., 2005) (Datum NAD27).

Appendix C continued.



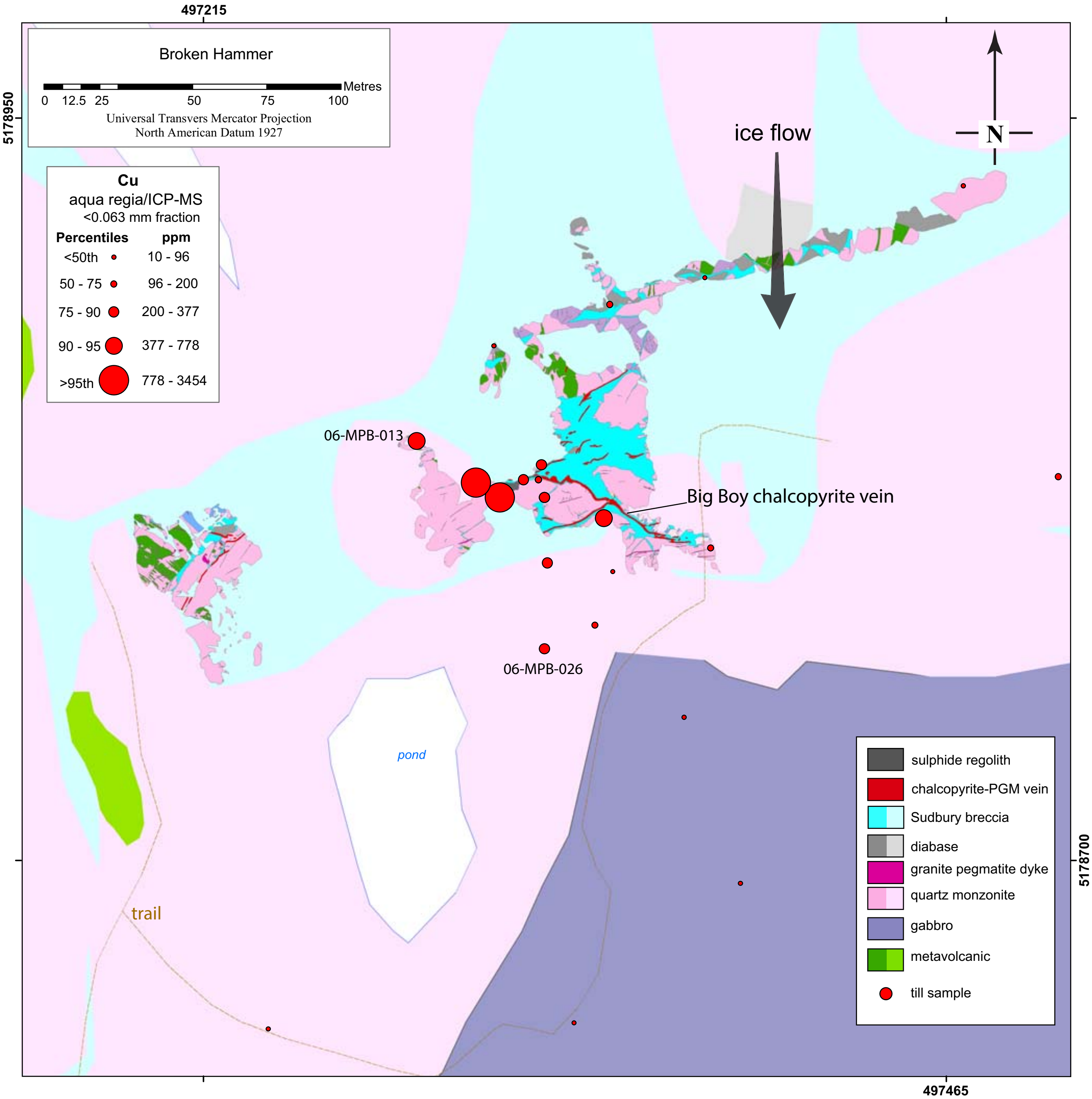
Map 2. Abundance of palladium in the <0.063 mm fraction of till proximal to the Broken Hammer occurrence (detailed bedrock geology from Peterson et al., 2004; regional bedrock geology from Ames et al., 2005) (Datum NAD27).

Appendix C continued.



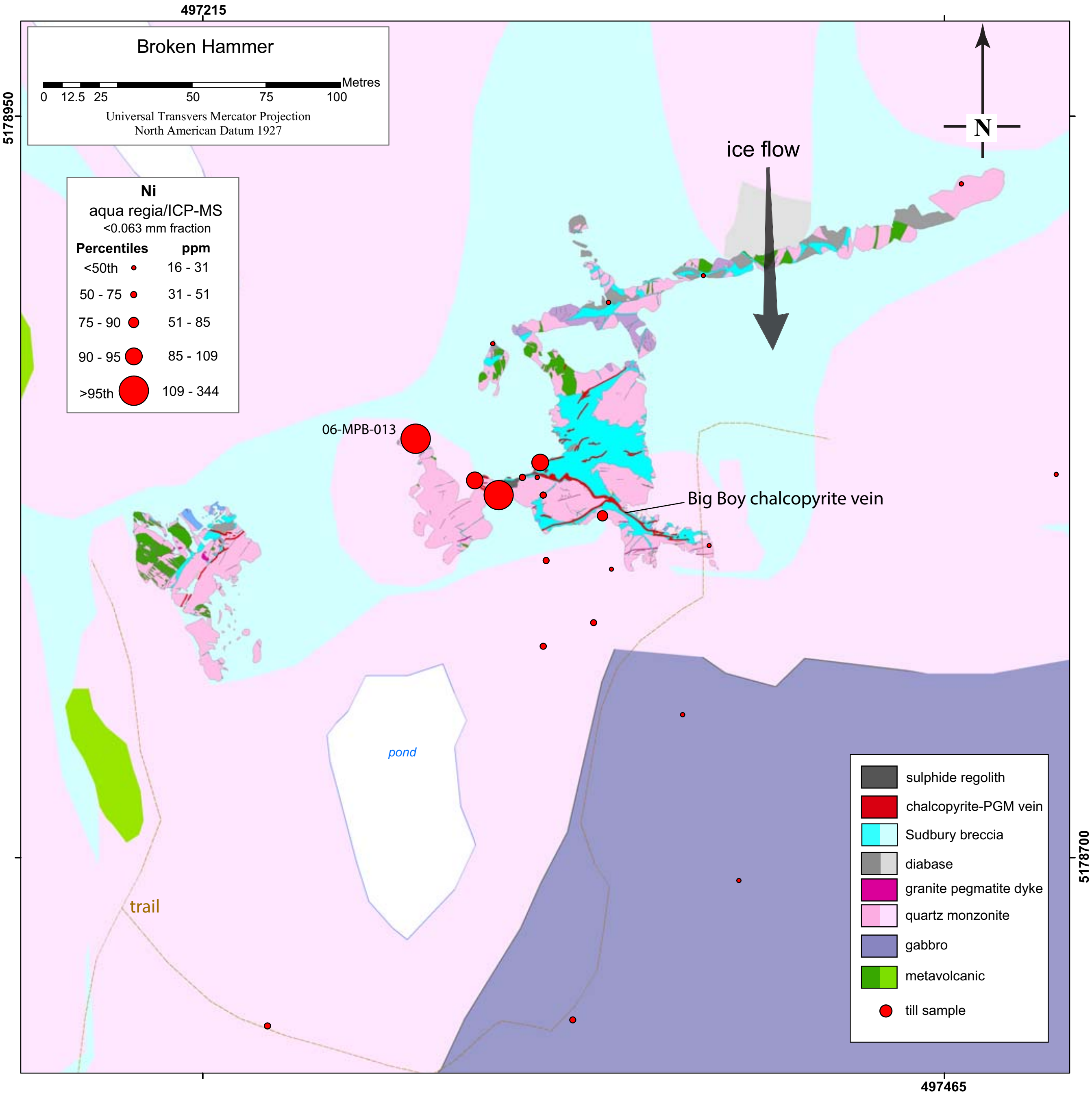
Map 3. Abundance of gold in the <0.063 mm fraction of till proximal to the Broken Hammer occurrence (detailed bedrock geology from Peterson et al., 2004; regional bedrock geology from Ames et al., 2005) (Datum NAD27).

Appendix C continued.



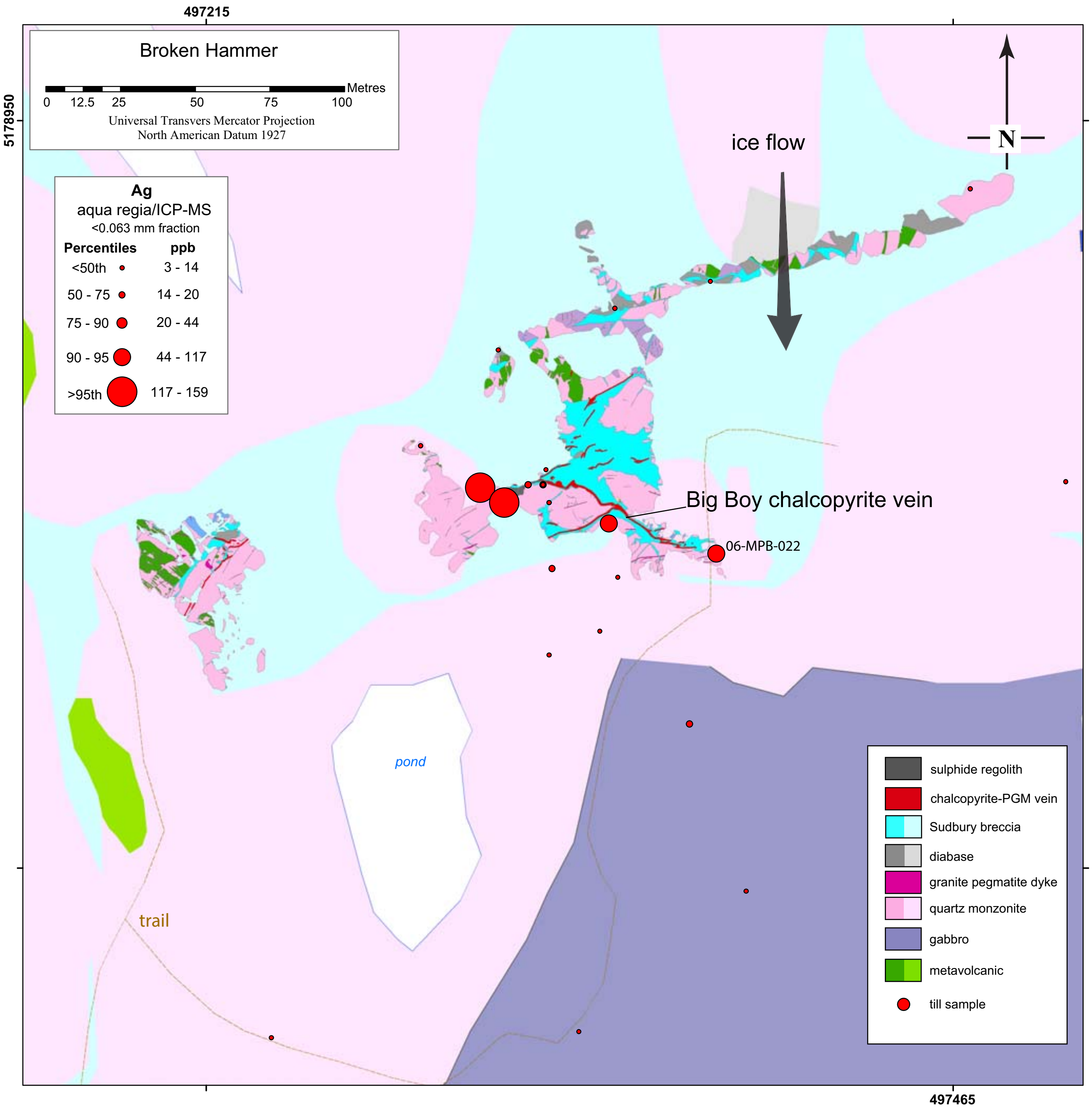
Map 4. Abundance of copper in the <0.063 mm fraction of till proximal to the Broken Hammer occurrence (detailed bedrock geology from Peterson et al., 2004; regional bedrock geology from Ames et al., 2005) (Datum NAD27).

Appendix C continued.



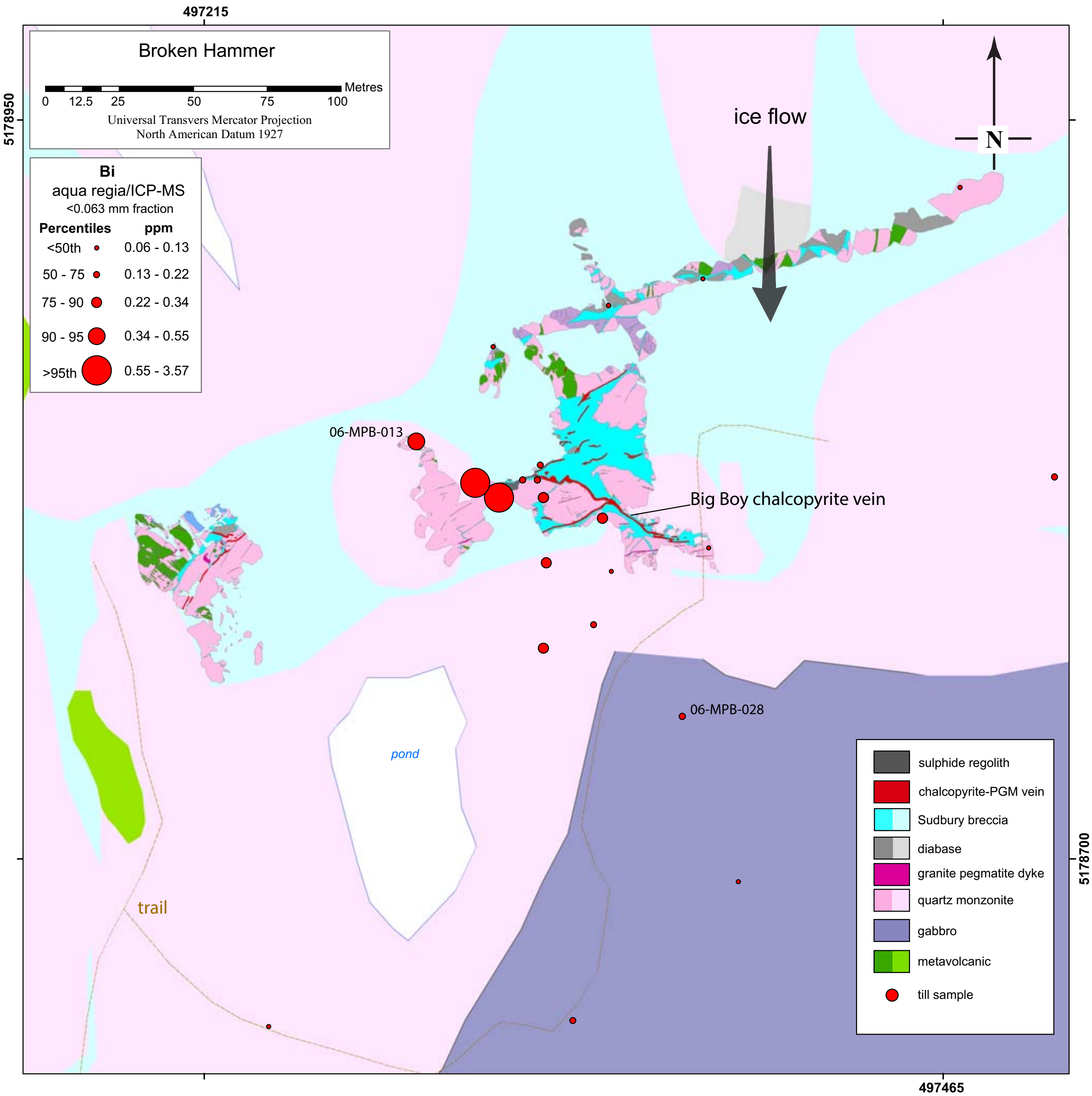
Map 5. Abundance of nickel in the <0.063 mm fraction of till proximal to the Broken Hammer occurrence (detailed bedrock geology from Peterson et al., 2004; regional bedrock geology from Ames et al., 2005) (Datum NAD27).

Appendix C continued.



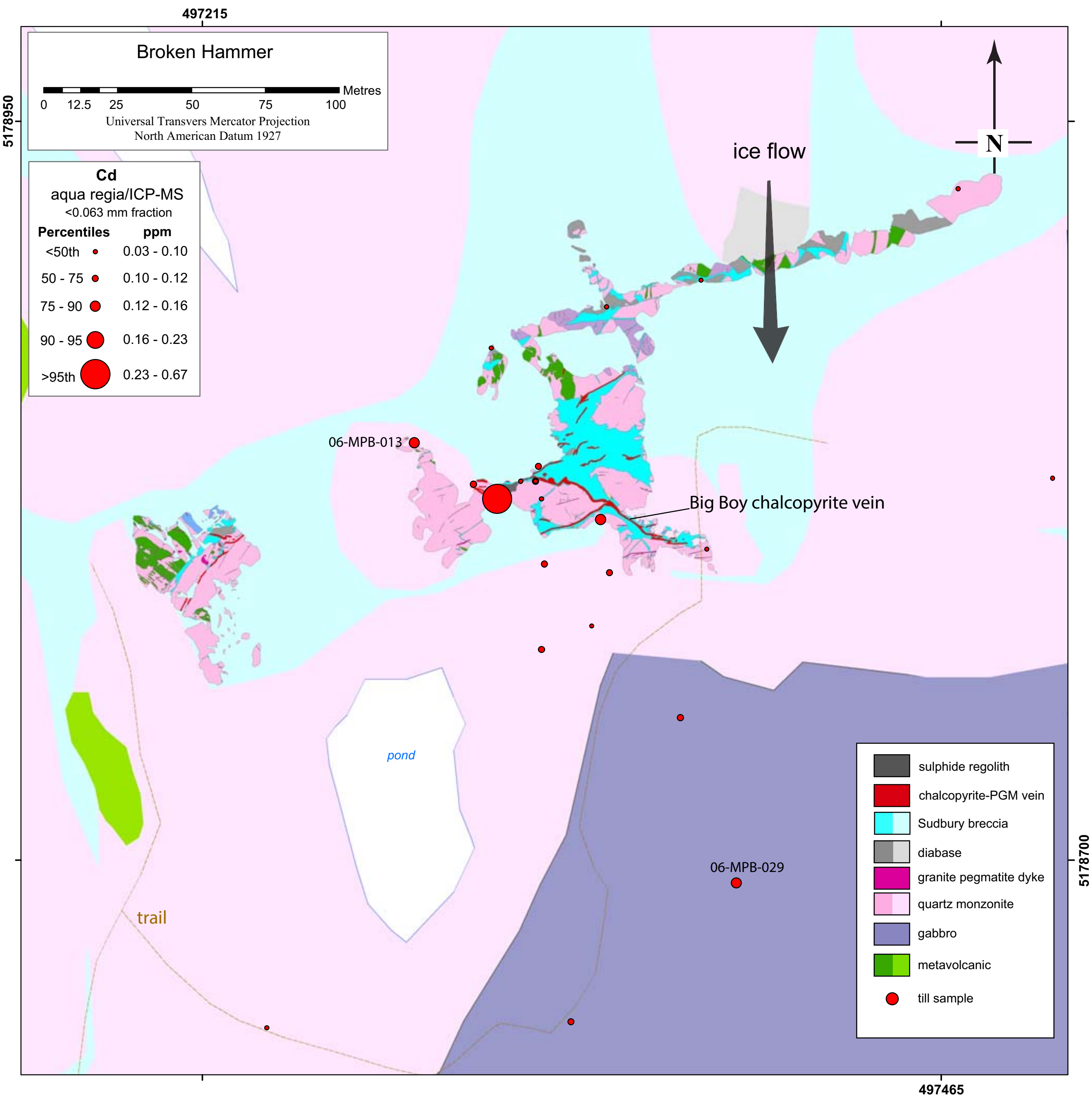
Map 6. Abundance of silver in the <0.063 mm fraction of till proximal to the Broken Hammer occurrence (detailed bedrock geology from Peterson et al., 2004; regional bedrock geology from Ames et al., 2005) (Datum NAD27).

Appendix C continued.



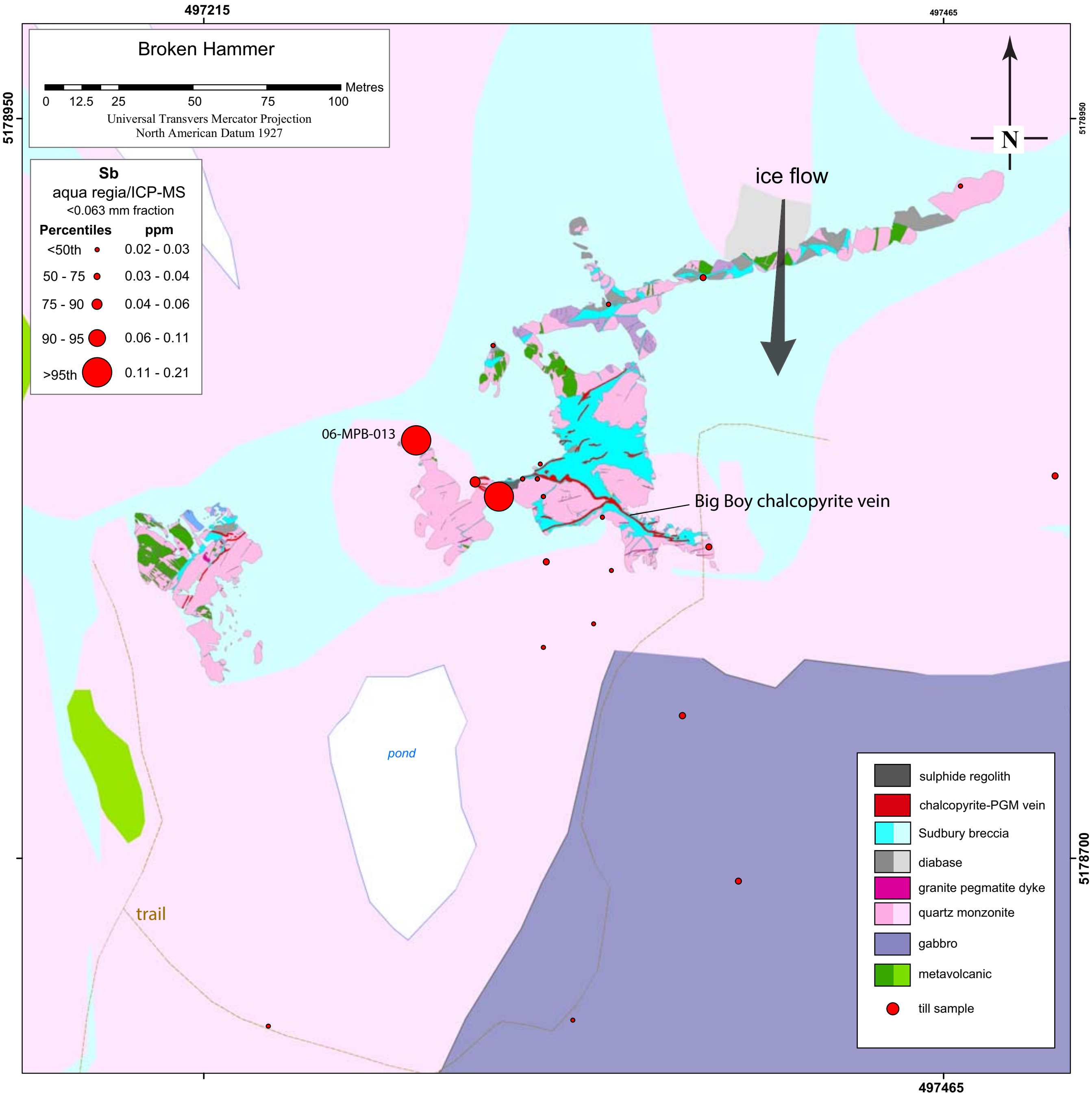
Map 7. Abundance of bismuth in the <0.063 mm fraction of till proximal to the Broken Hammer occurrence (detailed bedrock geology from Peterson et al., 2004; regional bedrock geology from Ames et al., 2005) (Datum NAD27).

Appendix C continued.



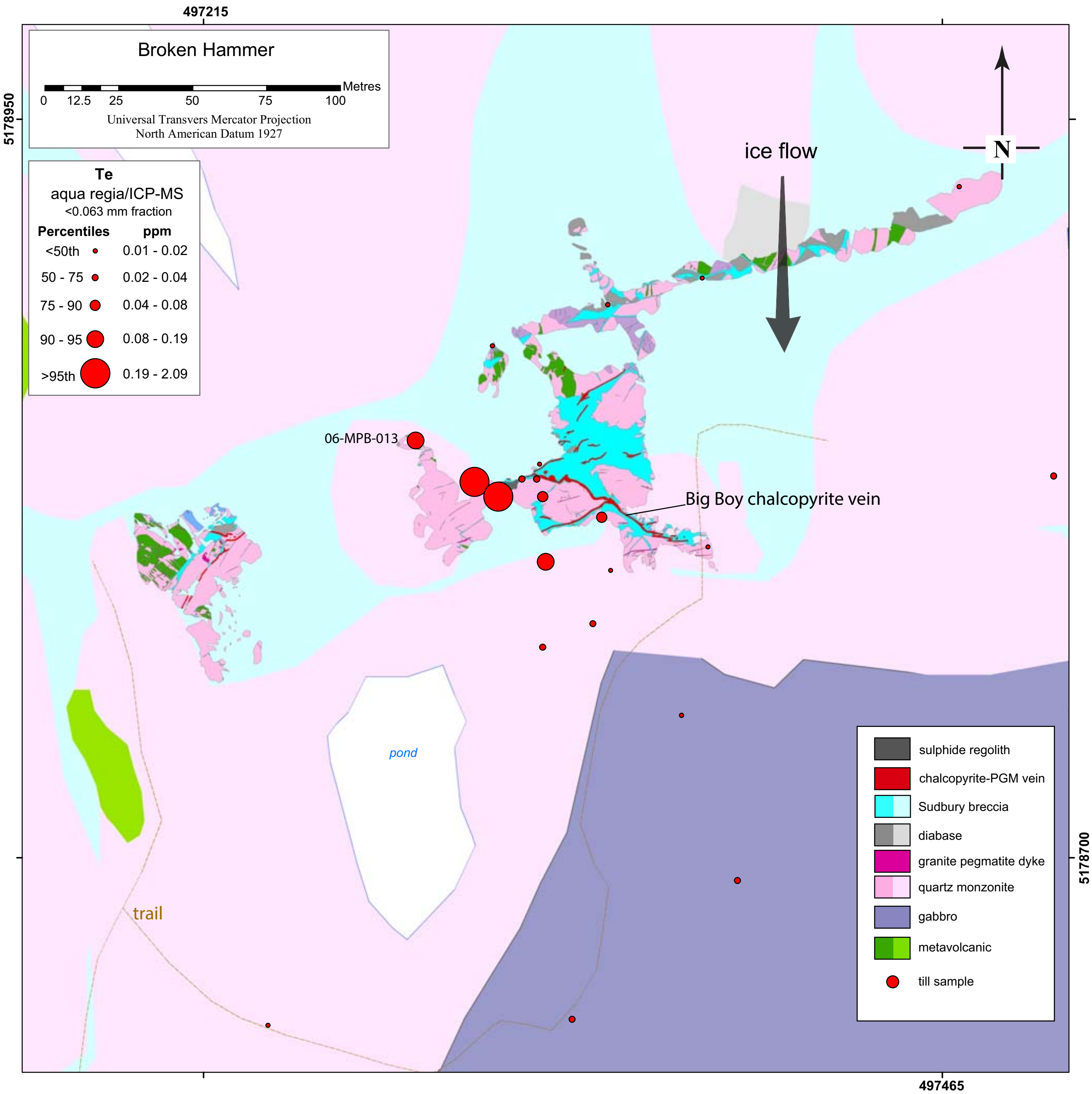
Map 8. Abundance of cadmium in the <0.063 mm fraction of till proximal to the Broken Hammer occurrence (detailed bedrock geology from Peterson et al., 2004; regional bedrock geology from Ames et al., 2005) (Datum NAD27).

Appendix C continued.



Map 9. Abundance of antimony in the <0.063 mm fraction of till proximal to the Broken Hammer occurrence (detailed bedrock geology from Peterson et al., 2004; regional bedrock geology from Ames et al., 2005) (Datum NAD27).

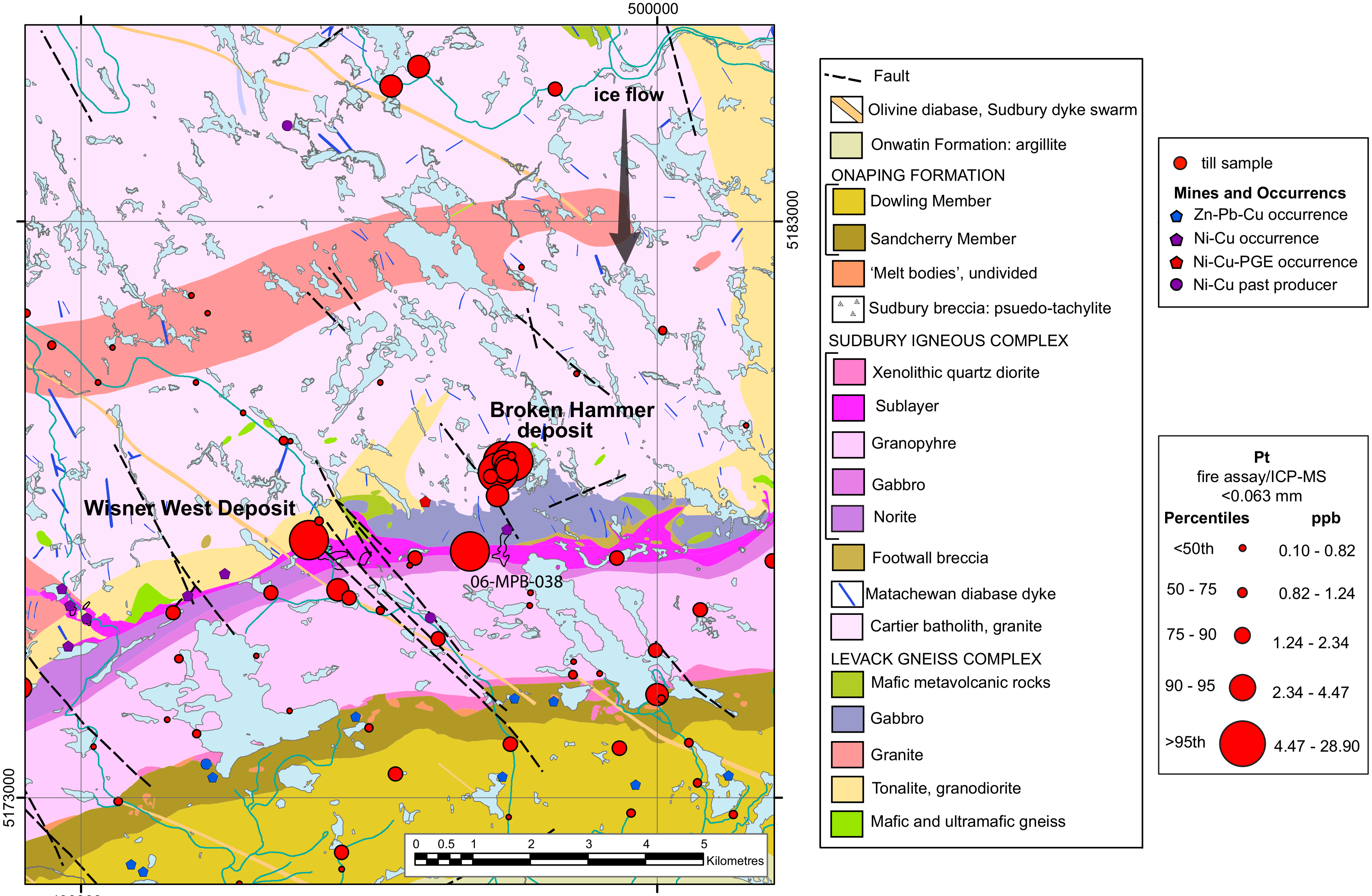
Appendix C continued.



Map 10. Abundance of tellurium in the <0.063 mm fraction of till proximal to the Broken Hammer occurrence (detailed bedrock geology from Peterson et al., 2004; regional bedrock geology from Ames et al., 2005) (Datum NAD27).

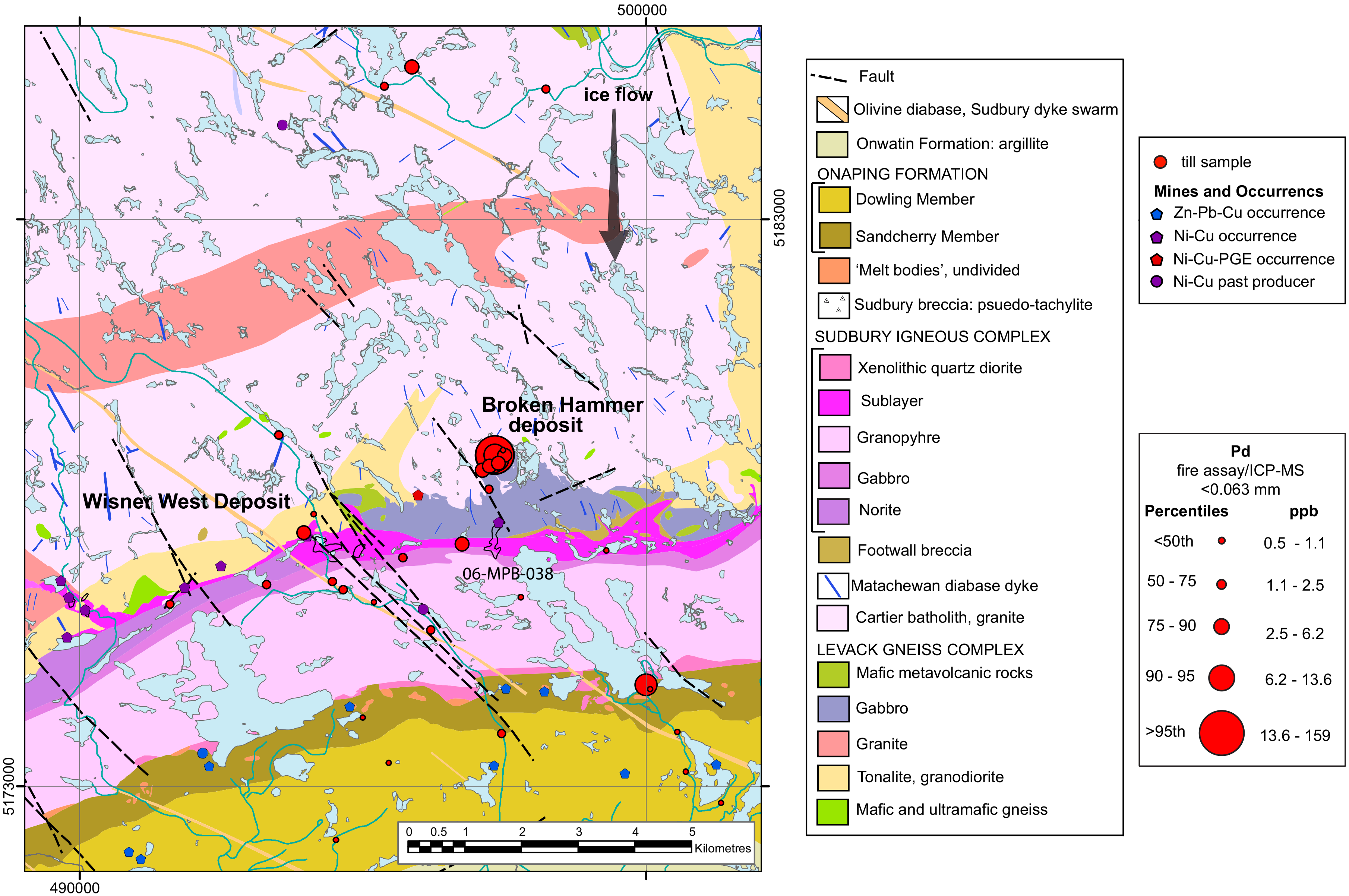
APPENDIX D

Regional-scale proportional dot maps of element abundance in the area surrounding the Broken Hammer and Wisner West sites



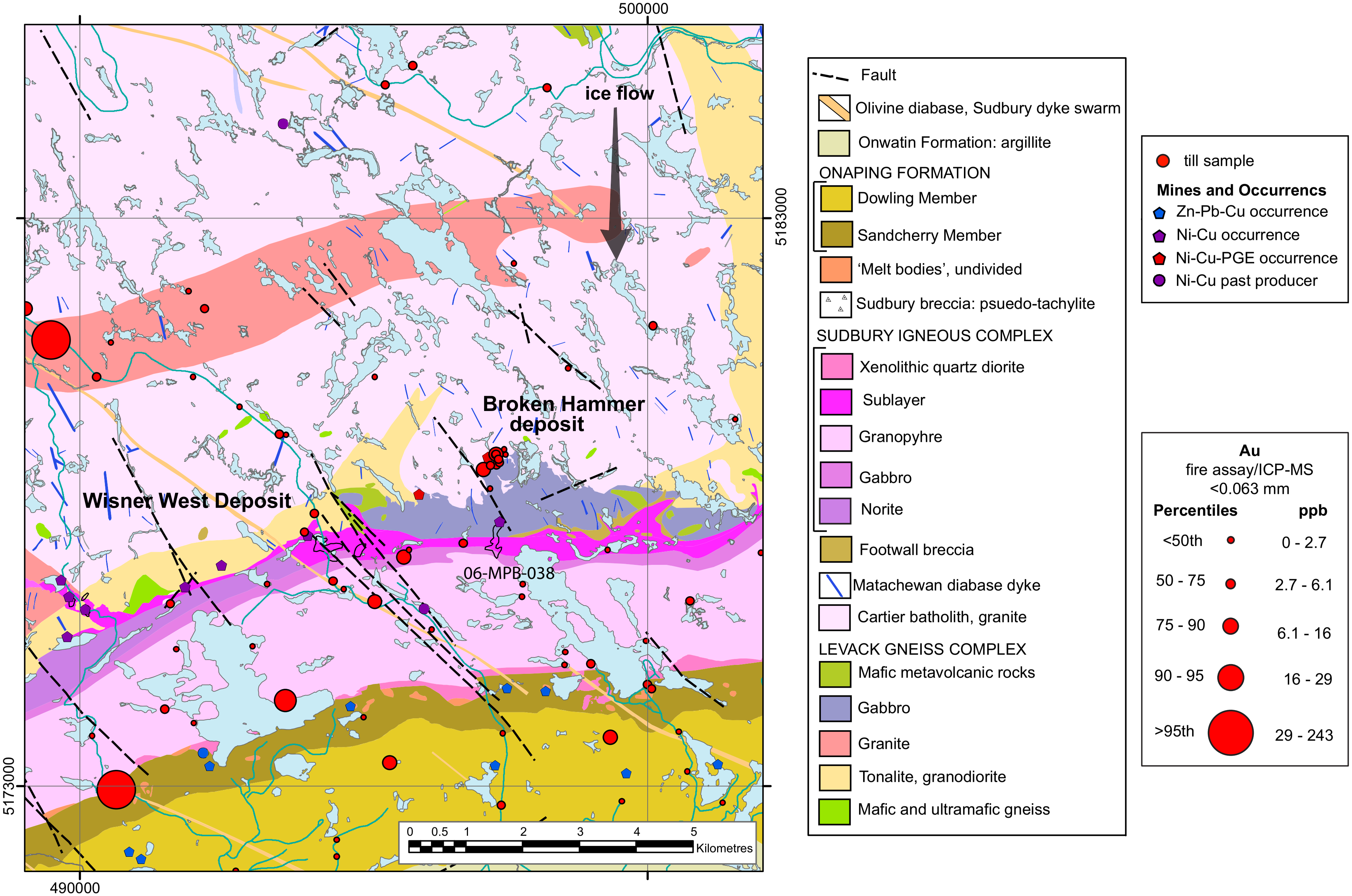
Map 11. Abundance of platinum in the <0.063 mm fraction of till in the region surrounding the Broken Hammer and Wisner West sites (bedrock geology from Ames et al., 2005) (Datum NAD27).

Appendix D continued.



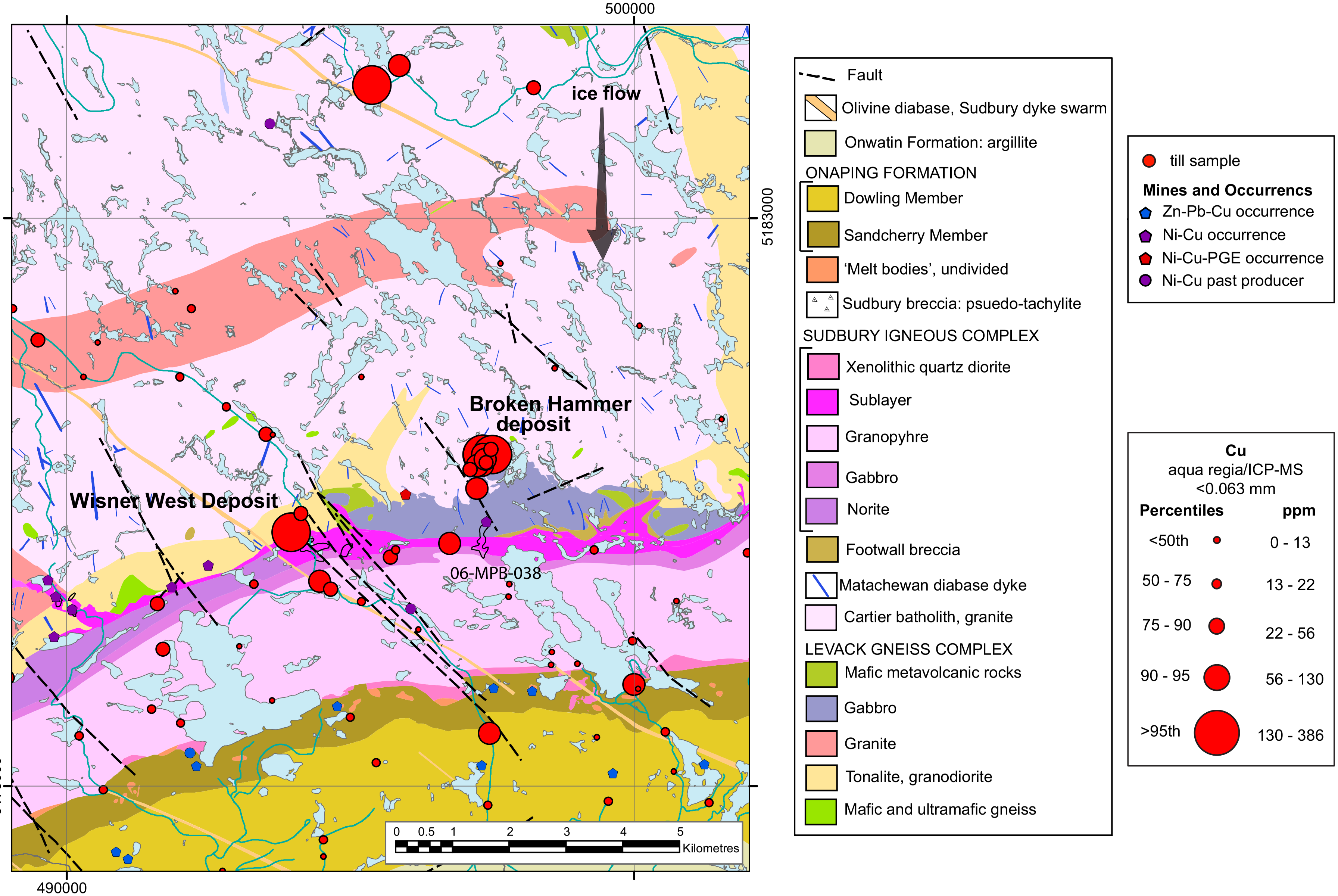
Map 12. Abundance of palladium in the <0.063 mm fraction of till in the region surrounding the Broken Hammer and Wisner West sites (bedrock geology from Ames et al., 2005) (Datum NAD27).

Appendix D continued.



Map 13. Abundance of gold in the <0.063 mm fraction of till in the region surrounding the Broken Hammer and Wisner West sites (bedrock geology from Ames et al., 2005) (Datum NAD27).

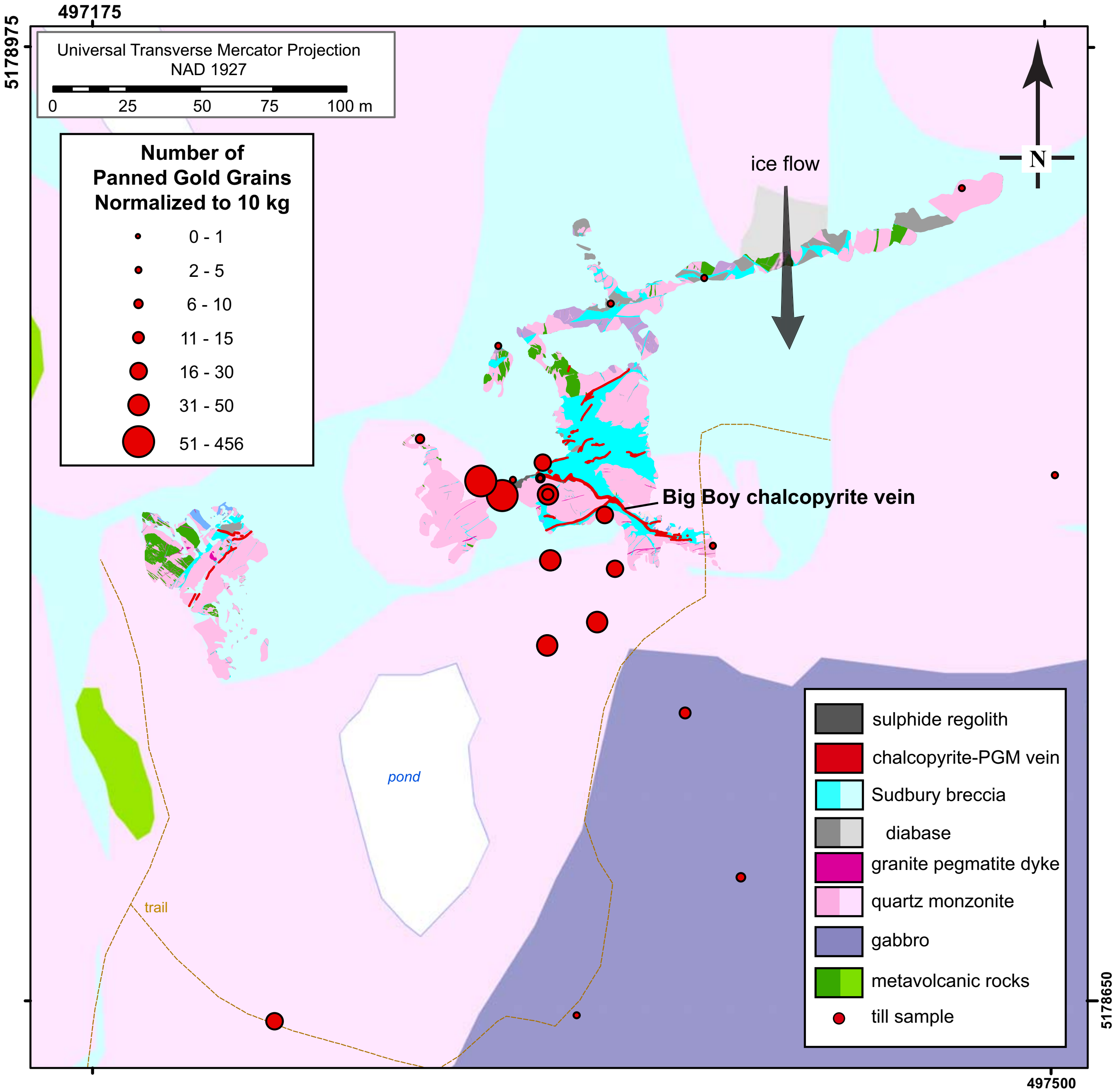
Appendix D continued.



Map 14. Abundance of copper in the <0.063 mm fraction of till in the region surrounding the Broken Hammer and Wisner West sites (bedrock geology from Ames et al., 2005) (Datum NAD27).

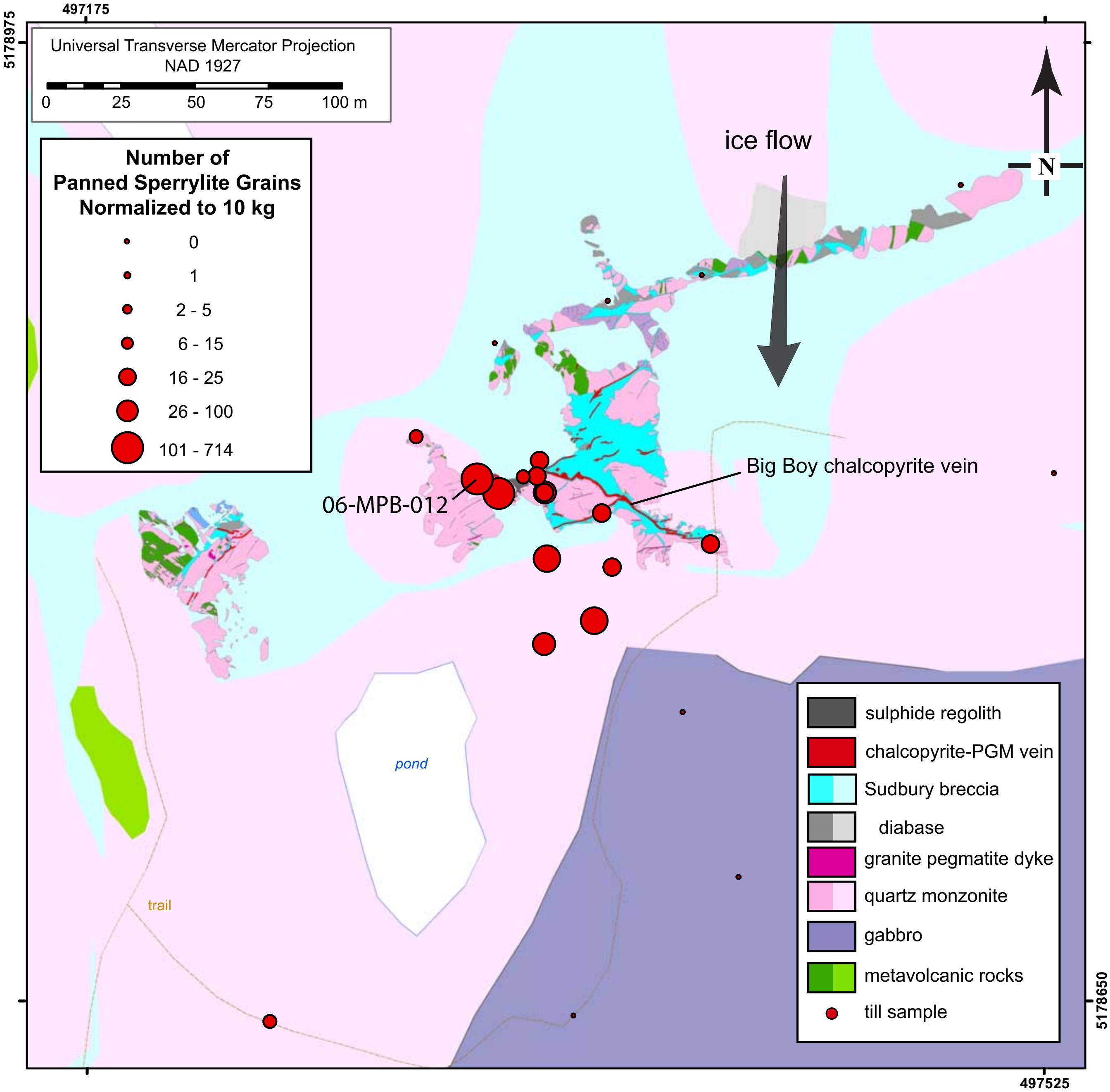
APPENDIX E.

Proportional dot maps of indicator mineral abundance in till proximal to the Broken Hammer site



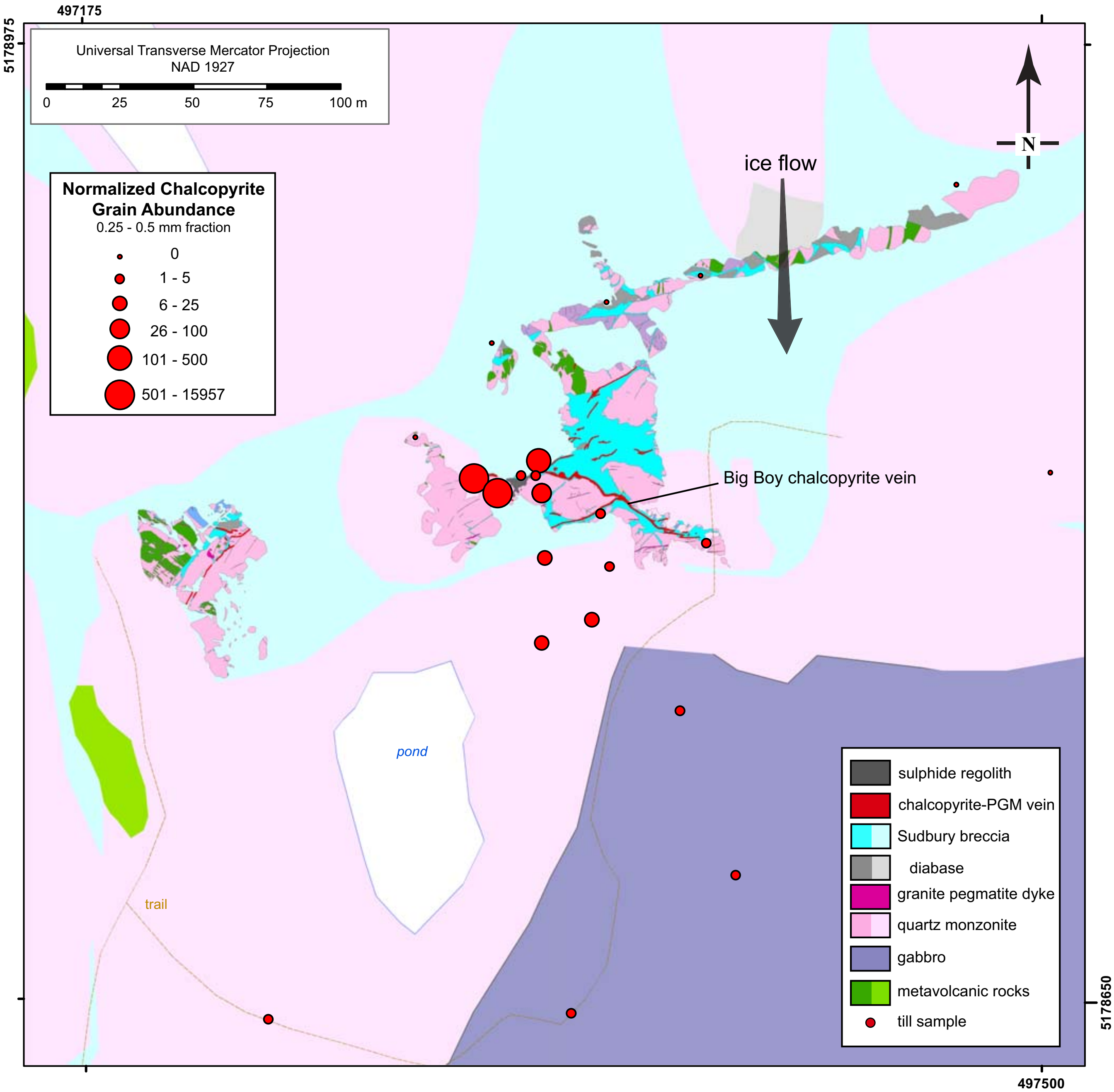
Map 15. Abundance of gold grains in till (normalized to a 10 kg sample weight) proximal to the Broken Hammer site (detailed bedrock geology from Peterson et al. 2004; regional bedrock geology from Ames et al., 2005) (Datum NAD27).

Appendix E continued.



Map 16. Abundance of sperrylite grains in till (normalized to a 10 kg sample weight) proximal to the Broken Hammer site (detailed bedrock geology from Peterson et al. 2004; regional bedrock geology from Ames et al., 2005) (Datum NAD27).

Appendix E continued.



Map 17. Abundance of chalcopyrite grains in till (normalized to a 10 kg sample weight) proximal to the Broken Hammer site (detailed bedrock geology from Peterson et al. 2004; regional bedrock geology from Ames et al., 2005) (Datum NAD27).