Till composition near Cu-porphyry deposits in British Columbia: Highlights for mineral exploration

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Abstract: Till orientation surveys were completed in the region of four Cu porphyry deposits in British Columbia with the objective of defining geochemical and mineralogical indicators of porphyry mineralisation buried by glacial sediments. We demonstrate that even if those deposits contain low to medium metal grades (e.g., 0.2 to 0.4 % Cu compared to an average crustal abundance of 0.0075 % Cu), they are reflected in the till composition with elevated concentrations of ore metals (Cu, Au, Mo) and pathfinder elements (Hg, Pb, Zn, Ag), and large grain counts of ore minerals (chalcopyrite, gold grains) and alteration minerals (e.g., epidote, andradite garnet, apatite) which are in contrast with surrounding regions devoid of mineralisation. These zones with elevated metal or mineral content in till define glacial dispersal trains that extend several kilometres down-ice from the bedrock mineralised sources. In this study, the shape of the dispersal trains is principally controlled by: 1) the ice-flow directions; and 2) the areal extent of the mineralisation exposed to glacial erosion which can comprise a cluster of sub-economic mineralised zones in the periphery of the main economic deposits. Using those porphyry indicators and existing till composition data sets from a region underlain by Late Triassic to Early Jurassic intrusions within the Quesnel terrane, we postulate that potential for Cu-Au porphyry style mineralisation exists within the Spout Lake pluton to the west of the Takomkane batholith and at the northern end of the Thuya batholith.

Introduction

Porphyry deposits are defined as "large, low- to medium-grade deposits in which primary (hypogene) ore minerals are dominantly structurally controlled and which are spatially and genetically related to felsic to intermediate porphyritic intrusions" (Kirkham, 1972; Sinclair, 2007). In Canada, 40 % of Cu, all Mo and 10 % of Au is produced from porphyry deposits (Sinclair, 2007). Porphyry deposits are predominantly found in orogenic belts and the Canadian Cordillera is no exception to this general rule as it includes a number of porphyry deposits which have been or are still in production (Fig. 1).

A hindrance to exploring for porphyry deposits in broad sectors of the Canadian Cordillera is the presence of an extensive and thick cover of glacial sediments which obscure prospective bedrock geology. Consequently, discoveries made from outcropping mineralisation have become increasingly rare. New efficient methods for detecting buried mineralisation need to be developed in this evolving context. To address this issue, the Geological Survey of Canada in collaboration with the British Columbia Geological Survey implemented an orientation till sampling survey in the region of four Cu-porphyry deposits in the Canadian Cordillera: Highland Valley Copper (Cu-Mo porphyry), Gibraltar (Cu-Mo porphyry) and Mount Polley (Cu-Au-Ag porphyry) mines and the Woodjam prospect (Cu-Mo-Au porphyry) (Fig. 1) . The sampling survey extended over a three year period (2011 to 2013) with the objective of defining key geochemical and mineralogical indicators of porphyry mineralisation that can be identified in till and related to buried mineralisation (Anderson et al., 2012a; Ferbey et al., 2014).

A total of 309 till samples (excluding field duplicate samples) were collected in this study and were geochemically analysed and processed for indicator minerals. Geochemical and mineralogical results were presented on posters and in oral presentations at conferences, and in departmental publications throughout the course of this activity (Anderson et al., 2012a, b, c; Plouffe et al., 2012, 2013a, c, 2014; Ferbey and Plouffe, 2014; Ferbey et al., 2014; Hashmi et al., 2014; Plouffe and Ferbey, 2015a). This paper presents the highlights of the work accomplished to date, provides an overview of the publications to be published in the future as part of this project, and discuss future research avenues that should be pursued to improve and develop mineral exploration methods for porphyry deposits in glaciated areas. As a general overview, we demonstrate that Cu-porphyry deposits with low to medium Cu grades (0.2 to 0.4 % Cu compared to an average crustal abundance of 0.0075 %; Rudnick and Gao, 2004) can be detected using a combination of geochemical and mineralogical analyses of the till matrix.

Porphyry mineralisation setting

Porphyry deposits within the Canadian Cordillera (Cu, Cu-Mo, Cu -Au, Au, W and Mo) occur principally in felsic to intermediate intrusive rocks associated to the Stikine and Quesnel volcanic arc terranes that were accreted to North America in the Middle Jurassic, with fewer porphyry deposits within the Wrangellia terrane (Fig. 1; Logan, 2013). Porphyry deposits formed during two episodes in two general tectonic settings: 1) in an island-arc setting, prior to accretion to North America, in Late Triassic to Middle Jurassic time, and 2) in a continental-arc setting, after accretion, in Late Cretaceous to Eocene time (McMillan and Panteleyev, 1995; McMillan et al., 1995, 1996; Logan, 2013). Logan and Mihalynuk (2014) presented the tectonic controls of a particular prolific period for the formation of Cu porphyry deposits in the Canadian Cordillera centred around 205 Ma when more than 90 % of the Cu deposits were formed.

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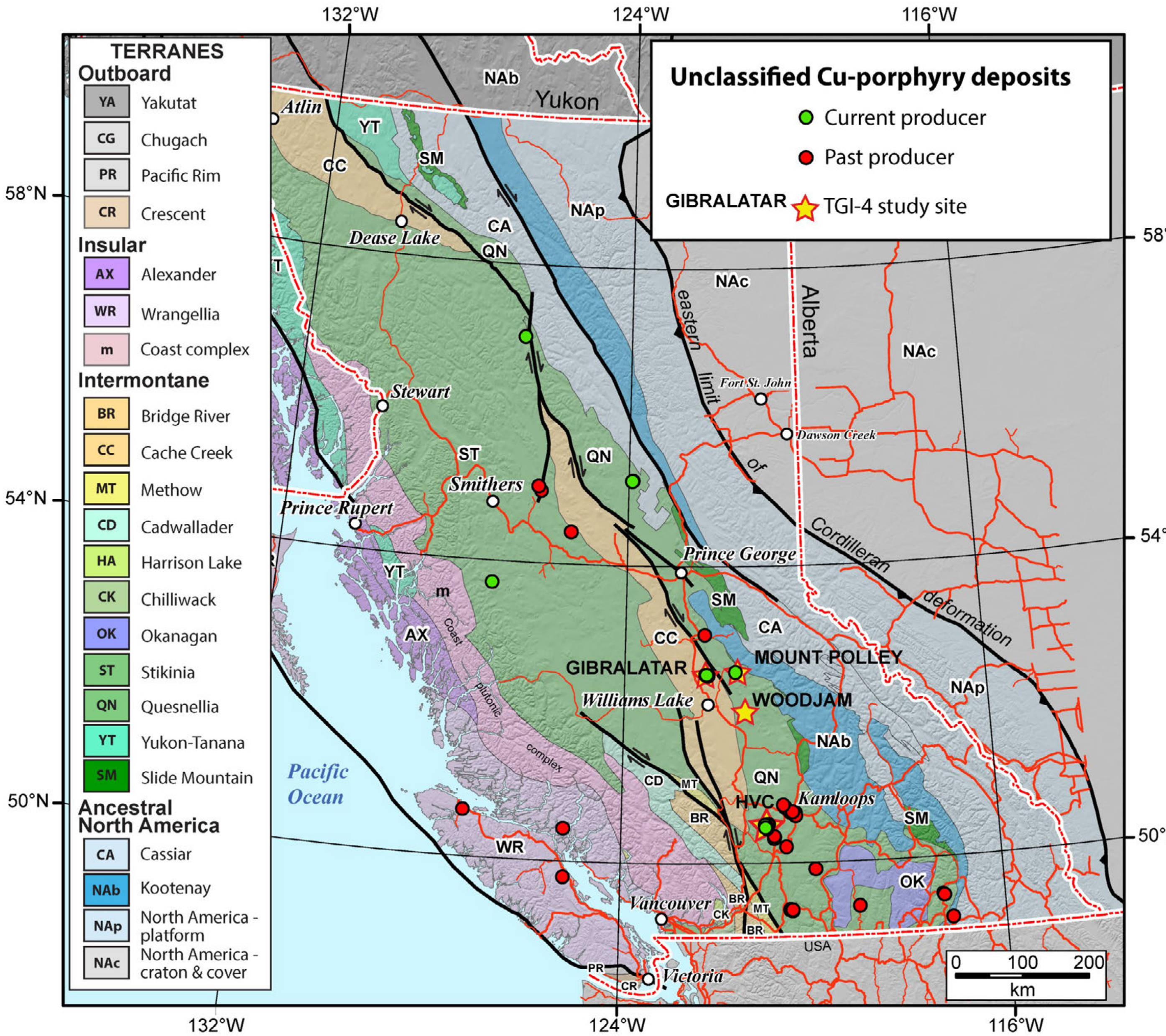

Figure 1 – Location of the four study sites, and of the past-producing and producing unclassified Cu-porphyry deposits (from MINFILE, 2015) depicted on the terrane map of British Columbia (Colpron and Nelson, 2011). HVC- Highland Valley Copper deposit.

The four Cu porphyry deposits investigated as part of this till sampling survey are part of the Quesnel terrane. Copper porphyry mineralisation at the four study sites is hosted in Late Triassic to Early Jurassic calcalkaline (Cu-Mo porphyry) to alkaline (Cu-Au porphyry) intrusions which intruded the coeval Nicola Group volcanic and associated sedimentary rocks. Chalcopyrite is one of the main Cu ore minerals at each site with lesser amounts of bornite. In the calcalkaline deposits, Mo is dominantly hosted in molybdenite.

The Highland Valley Copper Mine includes at least five calcalkaline Cu-Mo porphyry deposits hosted within the Guichon Creek batholith. A total of 1615.16 million tonnes of ore grading 0.40 % Cu and 0.010 % Mo were processed at the mine. In December 2012, the reserves were estimated at 697 million tonnes at 0.29 % Cu and 0.008 % Mo (Byrne et al., 2013).

The Mount Polley Mine is an alkaline Cu-Au-Ag porphyry deposit which has been in operation since 1997 with an interruption period of four years from 2001 to 2005. In addition to the mineralogy typical of Cu-porphyry deposits (i.e., chalcopyrite and bornite), Au and Ag occur as inclusions and as micro-scale grains that co-precipitated with sulfides (Pass, 2010). At this deposit, Au is more enriched in pyrite as compared to the Cu sulphides (Pass, 2010). A total of 80 million tonnes of ore were milled producing 452 million pounds of Cu, 695,000 ounces of Au, and 2.2 million ounces of Ag (Rees, 2013). As of January 2013, the reserves were estimated at 93 million tonnes grading 0.297 % Cu, 0.299 g/t Au, and 0.620 g/t Ag (Rees, 2013).

The Gibraltar Mine is a calcalkaline Cu-Mo porphyry deposit which has been in operation from 1972 to 1988 and from 2004 to present (Liles, 2005; van Straaten et al., 2013). The deposit is hosted within the Granite Mountain batholith. Because of the presence of Cache Creek rocks near the batholith and because of limited bedrock exposure which hinders the interpretation of contact relationship, the batholith was originally interpreted to be part of the Cache Creek terrane, which consists of ocean basin and oceanic arc rocks of Paleozoic to early Mesozoic age (e.g., Drummond et al., 1973, 1976; Bysouth et al., 1995). However, recent mapping has demonstrated that the batholith intrudes Nicola Group volcanic and sedimentary rocks and is part of the Quesnel terrane (Schiarizza, 2014, 2015). Combining past production and current resource, it represents 1.22 billion tonnes of ore with a Cu grade of 0.317 % and an estimated Mo grade of 0.010 % (van Straaten et al., 2013).

The Woodjam prospect includes five mineralised zones associated with emplacement of the Takomkane batholith and accompanying satellite intrusions at the northwestern limit of the batholith: Takom, Megabuck, Deerhorn, Southeast, and Three Firs. None of these zones have been mined. It includes porphyry mineralisation with alkaline and calcalkaline composition (del Real et al., 2013, 2014). To date, inferred resources for three mineralised zones at Woodjam are evaluated at 221.7 million tonnes of ore with Cu grades varying from 0.22 to 0.31 % Cu and 0.26 to 0.49 g/t Au (Sherlock et al., 2013; Sherlock and Trueman, 2013). Calculations of Mo reserves are not publically available for Woodjam.

Glacial sediment cover

The glacial sediment cover varies extensively at the four study sites. At Woodjam, none of the mineralisation is exposed at surface and only a portion of the alteration zone outcrops. Based on drill log data, unconsolidated sediment thickness reaches over 200 m over the deposit (J.W. Morton, pers. comm., 2014; see profiles in del Real et al., 2014). At the Gibraltar, Mount Polley and Highland Valley mines, at pre-mining time, the mineralisation was in large part covered by various thicknesses of glacial sediments (in other words mineralisation was subcropping) but in all cases a small part of the mineralisation was exposed at surface (in other words mineralisation was naturally outcropping) as reported in Rotherham et al. (1972), Casselman et al. (1995), Byrne et al. (2013), and Rees (2013). Any mineralised zone that was protected from glacial erosion represents a limiting factor in the application of till composition for the detection of buried mineralisation (Plouffe et al., 2012). This is the case at Woodjam where one of the mineralised zone (Three Firs) is in part covered by basalt correlated to the Oligocene-Pliocene Chilcotin Group that can be up to 20 m thick (Bissig et al., 2013). At Highland Valley, pre-glacial sediments partly cover the Valley deposit and probably completely cover the J.A. deposit (Bobrowsky et al., 1993; Byrne et al., 2013). The Chilcotin Group basalt at Woodjam and the pre-glacial sediments at Highland Valley acted as a shield which protected part of the mineralisation from glacial erosion. Therefore, none of the protected mineralisation is reflected in the till composition.

Glacial history

The interpretation of the glacial history for the four study sites is based on previous studies plus the current investigation of the ice-flow direction indicators. All of the four sites were covered by the Cordilleran Ice Sheet during the Late Wisconsinan Fraser glaciation. At the onset of glaciation, valley glaciers coalesced into piedmont glaciers in the Coast and Cariboo mountains (Tipper, 1971a, b). Valley glaciers also formed in isolated mountain ranges within the Interior Plateau (e.g., Clague, 1989; Plouffe, 2000). The first glaciers to cover the three northern most study sites were derived from the Cariboo Mountains and were generally advancing to the west to southwest. At glacial maximum, glaciers from the Coast and Cariboo Mountains coalesced over the Interior Plateau forming an east-west ice divide around the 52° latitude from which ice was flowing to the north and south. This ice divide is visible on the provincial compilation map of ice-flow indicators (Ferbey and Arnold, 2013; Ferbey et al., 2013). Consequently, at the three northern sites, there was a second phase of ice flow to the north to northwest which originated from the ice divide. Only in the Gibraltar Mine region, we have found evidence of a third ice movement to the southeast, the origin and timing of which is still unclear. The net implication of these multiple ice-flow movements is that the geochemical or mineralogical signal in till derived from mineralisation might have been transported by any combination of these glacial transport vectors.

Regional surficial geology investigations plus our own field studies in the Highland Valley Copper deposit region, have defined a single vector of ice flow to the south to southeast which was derived principally from the ice divide at the 52° latitude (Fulton, 1975; Ryder, 1976; Bobrowsky et al., 2002; Plouffe et al., 2013a, b).

Methods

Field work involved sampling till, measuring ice-flow indicators on bedrock outcrops and making observations for the production of surficial geology maps. Till sampling was completed following procedures outlined in Spirito et al. (2011) with the objective of obtaining samples not only down-ice but in all directions from the known mineralisation. This approach is used to define the extent of glacial dispersal and to demonstrate that the geochemical or mineralogical enrichment in till which defines a glacial dispersal train stands out above regional background values. Two till samples were collected at each sampling site: a large (ca. 10 kg) and small (ca. 2 kg) sample.

The small sample was shipped to the Sedimentology Laboratory of the Geological Survey of Canada and was processed to separate the silt and clay-sized fraction (<0.063 mm) by dry sieving and the clay-sized fraction (<0.002 mm) by decantation and centrifuging (Girard et al., 2004). Both fractions were submitted for geochemical analyses in a commercial laboratory (ACME Analytical Laboratories, Bureau Veritas Company, Vancouver, BC) which included two analytical packages: 1) 0.2 g aliquots were digested with lithium metaborate/tetraborate, fused at 980°C, dissolved in 5 % HNO_3 and then analysed by inductively coupled plasma emission spectrometry and mass spectrometry (ICP-ES and ICP-MS), and 2) 0.5 of clay sized (<0.002 mm) material and 30 g of silt plus clay sized (<0.063 mm) material were diluted in a HCl and HNO_3 solution (ratio 1:1, modified aqua regia) and analysed by ICP-MS (Fig. 2A). Large silt and clay aliquots (30 g) were submitted for Au analyses by ICP-MS to reduce the nugget effect (Harris, 1982; Stanley, 2008) attributed to fine gold grains heterogeneously distributed in the silt-sized material of the till matrix which generally result in low analytical precision. A combination of field duplicates, laboratory duplicates (blind duplicate) and standards were submitted with the routine samples to monitor sampling site variability, analytical precision and accuracy, respectively.

The large samples were processed to recover the heavy (>3.2 specific gravity (s.g.)) and mid-density (2.8-3.2 s.g.) mineral fractions

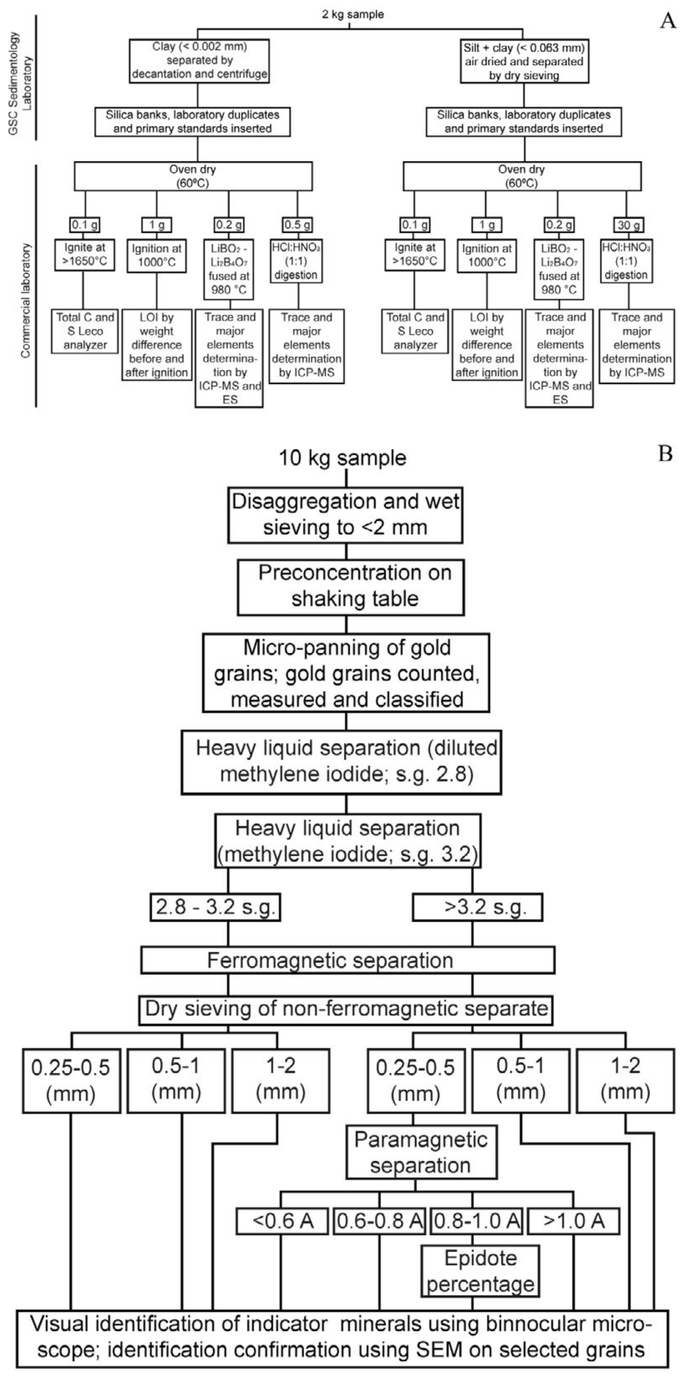

Figure 2 – Flow charts showing the procedures followed for:
(A) geochemical analyses;
(B) heavy mineral separation and indicator mineral identification.

and identify indicator minerals at Overburden Drilling Management Limited (Ottawa, ON) following the protocols adopted at the Geological Survey of Canada (see Plouffe et al. (2013b) for the details of the methodology) and outlined in Figure 2B. Quality assurance and quality control samples were submitted along with the routine samples and included: 1) blank samples from weathered granite to monitor potential cross-contamination, 2) field duplicate samples to monitor sampling site variability, and 3) spiked samples to evaluate the precision of the heavy mineral separation and indicator mineral identification procedures. In addition, a limited number of heavy mineral concentrates were re-numbered and re-submitted for mineral identification to evaluate the precision of the indicator mineral counts.

Geochemical and mineralogical analytical results obtained for this study will be available via an open file report (A. Plouffe and T. Ferbey, work in progress, 2015).

Results and interpretation: an overview

Interpretation of the till geochemical and mineralogical data, taking in consideration the reconstructed ice-flow histories, has important implications for mineral exploration for porphyry deposits in glaciated areas. Key highlights are presented below.

Porphyry mineralisation can be detected based on multi-element enrichment in till.

At the four study sites, Cu-porphyry mineralisation is reflected by a high Cu content in the clay-sized fraction of till down-ice from the mineralised zones (Figs. 3 and 4; Plouffe et al., 2011a, 2013a; Plouffe and Ferbey, 2015a). The high Cu concentrations in till near the known mineralised zones stands out above regional background Cu content of till and reaches concentrations greater than 380 ppm at Gibraltar, Mount Polley and Woodjam, and greater than 990 ppm at Highland Valley Copper. These high Cu concentrations define glacial dispersal trains with various lengths; one to two kilometres at Woodjam but over four kilometres at Mount Polley. The areal extent and shape of the Cu dispersal is in part related to the extent of the bedrock mineralisation exposed to glacial erosion (Plouffe et al., 2012). For example, the large amoeboid dispersal train of Cu in till at Gibraltar is in part related to a cluster of Cu porphyry mineral occurrences in the region that were glacially eroded (Fig. 3).

At calc-alkaline Cu-Mo porphyry deposits, till contains up to 8 ppm Mo (Fig. 5; Plouffe et al., 2014). At Gibraltar, the areas of Mo and Cu rich till are similar in size and shape (Figs. 3 and 5). At the Mount Polley alkaline Cu-Au-Ag porphyry deposit, till contains up to 90 ppb Au defining a Au glacial dispersal train of over 8 km extending down-ice to the northwest (Fig. 6; Hashmi et al., 2014, in press a, b).

High commodity metal contents in till near porphyry deposits can be found in association with high pathfinder element contents. Such is the case at Gibraltar where elevated Ag and Zn (Plouffe et al., 2011a, 2014) and at Mount Polley where elevated Zn and Hg concentrations (Hashmi et al., 2014, in press a) have been identified in till at the periphery of the main deposits. These patterns in the till reflect metal zoning associated to the main mineralisation. These results indicate that porphyry mineralisation that was exposed to glacial erosion and is now partly buried by glacial sediments, can be detected based on elevated multi-element contents in till.

Ore minerals are present in till down-ice from porphyry deposits.

Analogous to high trace element contents identified in till in the region of the porphyry deposits, ore minerals associated with porphyry mineralisation are present in till. Chalcopyrite is a key ore mineral in most Cu porphyry deposits in British Columbia and it has been recovered from till samples at all four study sites (Fig. 7). It is present and

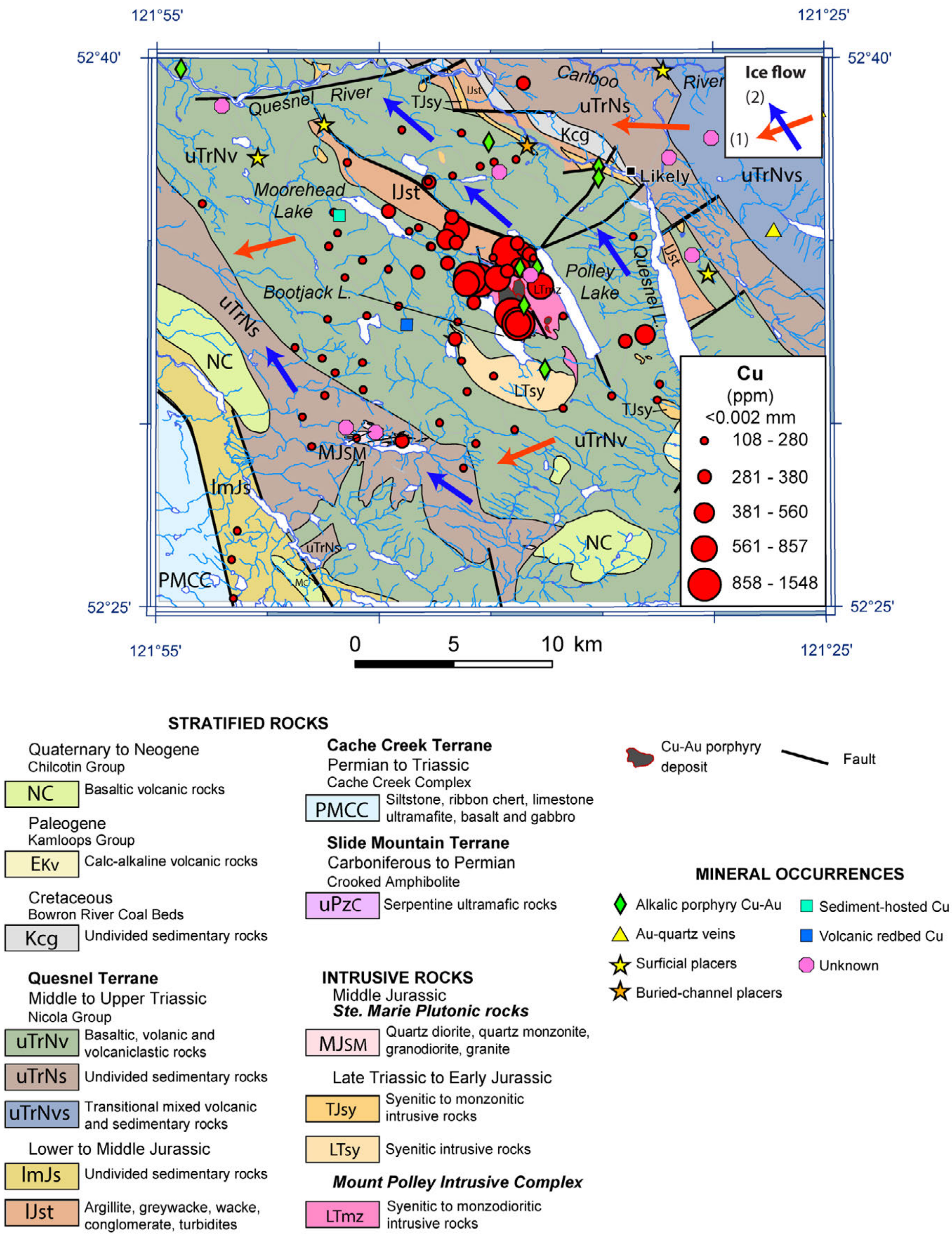

Figure 3 – Copper in the clay-sized fraction of till at the Mount Polley deposit analysed by ICP-MS after an HCl : HNO_3 leach (1:1) (modified from Hashmi et al., in press a). Bedrock geology simplified from Massey et al. (2005) and Logan et al. (2007, 2010).

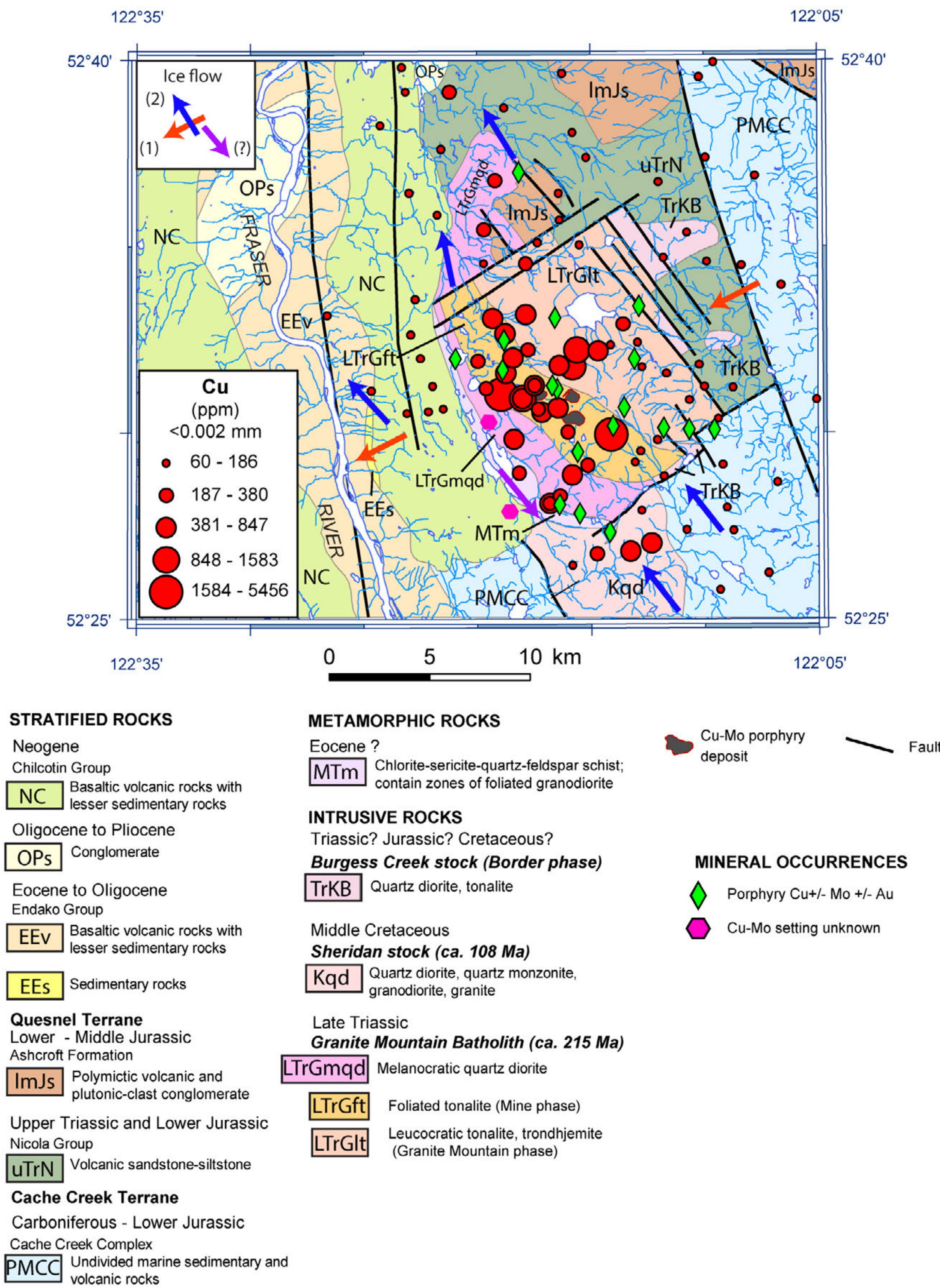

Figure 4 – Copper in the clay-sized fraction of till at the Gibraltar deposit analysed by ICP-MS after an HCl : HNO_3 leach (1:1). Bedrock geology simplified from Ash et al. (1999), Massey et al. (2005) and Schiarizza (2014).

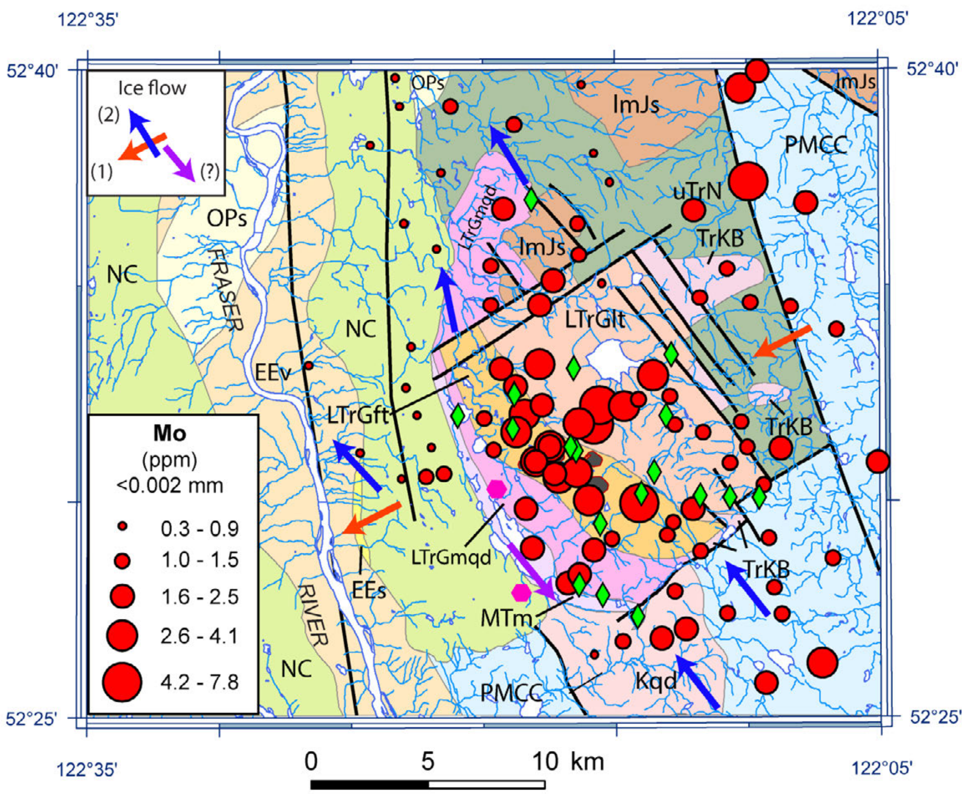

Figure 5 – Molybdenum in the clay-sized fraction of till at the Gibraltar deposit analysed by ICP-MS after an HCl : HNO_3 leach (1:1) (modified from Plouffe et al., 2014). Bedrock geology legend is the same as Figure 4.

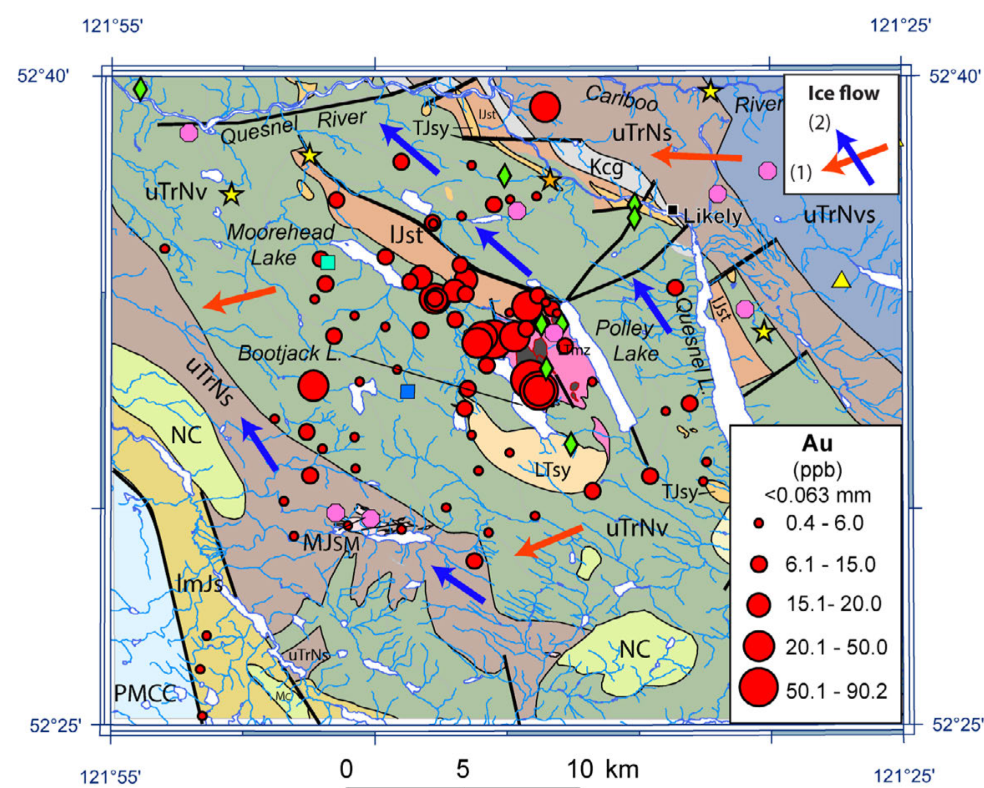

Figure 6 – Gold in the silt plus clay-sized fraction of till at the Mount Polley deposit analysed by ICP-MS after an HCl : HNO_3 leach (1:1) (modified from Hashmi et al., in press a). Bedrock geology legend is the same as Figure 3.

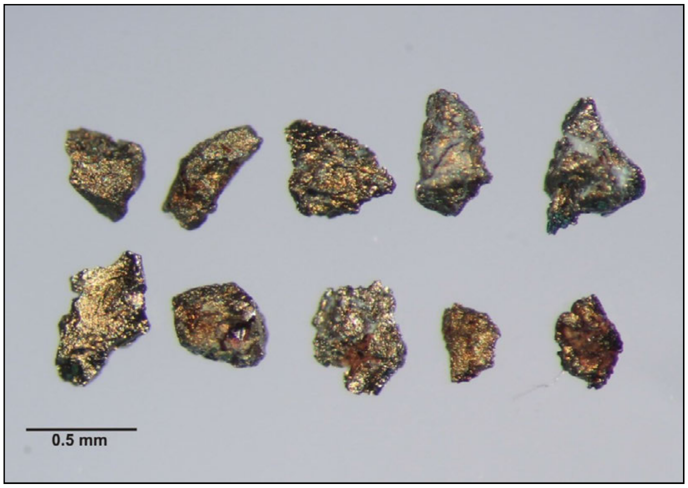

Figure 7 – Chalcopyrite grains (0.25-0.5 mm) recovered from till in the region of the Highland Valley Copper mine (modified from Plouffe et al., 2013a)

more abundant in till down-ice from Cu mineralised zones compared to surrounding regions (Figs. 8 and 9). At Mount Polley, the abundance of chalcopyrite grains in the heavy mineral fraction (0.25-0.5 mm and >3.2 specific gravity) define a dispersal train which extends over six kilometres down-ice (northwest) from the known mineralisation (Fig. 10; Hashmi et al., 2014, in press a, b). At the same site, the Au mineralisation is well reflected in till by a Au grain dispersal train that extends over five kilometres down-ice (Fig. 11). In contrast, molybdenite was not identified in till near any of the Cu-Mo porphyry deposits and consequently, this mineral has limited application for the detection of buried porphyry mineralisation. The absence of molybdenite in till could be related to a combination of the following factors: 1) its weathering in till since deglaciation or 2) its low abundance to absence in the mineralised bedrock that was exposed to glacial erosion and 3) its inability to survive glacial erosion and transportation due to its extreme softness (hardness=1).

The ore mineral chalcopyrite can be considered a key porphyry Cu indicator mineral in till. Likewise, gold grains can be indicative of Cu-Au porphyry mineralisation and can be present along with chalcopyrite grains.

Alteration minerals are present in tills near porphyry deposits.

Porphyry deposits are characterized by the presence of alteration zones that occur peripheral to ore mineralisation (Lowell and Guilbert, 1970). Alteration zones progress outward from a potassic core (K-feldspar, biotite, ± amphibole, ± magnetite, ± anhydrite) which is shelled by phyllic (quartz-sericite-pyrite), argillic (quartz, illite, pyrite, ± kaoloin, ± smectite, ± montmorillonite, ± smectite), and propylitic (epidote-chlorite-calcite, ± albite, ± pyrite) zones (Lowell and Guilbert, 1970; Sinclair, 2007). These alteration zones have been defined at Highland Valley Copper (Casselman et al., 1995; Byrne et al., 2013), Mount Polley (Fraser, 1994; Rees, 2013) and Gibraltar (Drummond et al., 1973, 1976).

Certain alteration minerals are found to be abundant in till down-ice from porphyry deposits. Because the alteration zones in porphyry deposits are larger than the mineralised zones, they potentially represent a larger exploration target and their associated mineralogical signature in till can be aerially extensive. For example, at Gibraltar and Woodjam, large regions extending over 10 km from mineralised zones are characterized by abundant green epidote in till which is in contrast with surrounding regions (Figs. 12, 13, and 14). The epidote in till is thought to be derived at least in part from the propylitic alteration (Plouffe et al., 2013a). On the other hand, at Highland Valley Copper, epidote in till is present in amounts greater than 70 % over a large area probably because of the extensive regional moderate to strong chlorite (epidote) alteration in the Guichon Creek batholith (cf. Casselman et al., 1995; Fig. 15). At Mount Polley, andradite garnet and apatite potentially derived from the porphyry alteration zones (Rees, 2013) are found to be abundant in a limited number of till samples up to at least 2.6 kilometres down-ice (northwest) from the deposit (Hashmi et al., in press a, b). Lastly, jarosite, common in supergene enrichment zones associated with Cu porphyry deposits (e.g., Averill, 2011; Kelley et al., 2011), was identified in till down-ice of mineralised zones at Mount Polley (Hashmi et al., in press a) and Woodjam (Ferbey and Plouffe, 2014).

Minerals common in alteration zones (e.g., epidote, andradite, apatite) or supergene enrichment (e.g., jarosite) associated to porphyry deposits have the potential to become porphyry indicator minerals in till. However, these minerals may not be unique to porphyry deposits and therefore, the physical and compositional attributes of minerals derived from porphyry alteration zones versus other barren sources need to be characterized. Defining the physical and chemical characteristics of alteration minerals will serve to define the presence of buried alteration zones which potentially can represent larger exploration targets compared to the mineralised zone enriched in commodity metals.

Interpretation of till composition needs to take into account reconstruction of local ice-flow history.

The importance of understanding the ice-flow history to interpret till composition as applied to mineral exploration has long been recognized (e.g., DiLabio and Coker, 1989; Kujansuu and Saarnisto, 1990; Bobrowsky et al., 1995; Paulen, 2013). Interpretation of the till geochemical and mineralogical data from this project is no different. For example, the distribution of geochemical and mineralogical porphyry indicators in till at Mount Polley requires consideration of two phases of ice-flow which have formed palimpsest dispersal trains influenced by the first (southwest) and second (northwest) phase of ice movement (Hashmi et al., 2014, in press a, b). At Gibraltar, the extensive amoeboid dispersal trains defined by till geochemistry and mineralogy (Plouffe et al., 2014) reflect, as indicated above, the presence of a cluster of Cu porphyry mineralised zones as well as the complex ice-flow history which included ice movements to the southeast, west and northwest. Amoeboid dispersal trains are known to occur in regions with complex ice-flow histories (e.g., Stea 1989; Shilts, 1993; Trommelen et al., 2013).

Composition of alteration minerals could provide information on porphyry mineralisation source.

At Mount Polley, magnetite-rich hydrothermal alteration is found in close association with Cu mineralisation (Rees, 2013). Magnetite grains from till, the magnetite breccia (mineralised) and the monzonite (unmineralised) from Mount Polley were analysed by laser ablation – inductively coupled plasma mass spectrometry (LA-ICP-MS) at the University of Victoria to test if the hydrothermal magnetite could have a different composition and have different physical characteristic com-

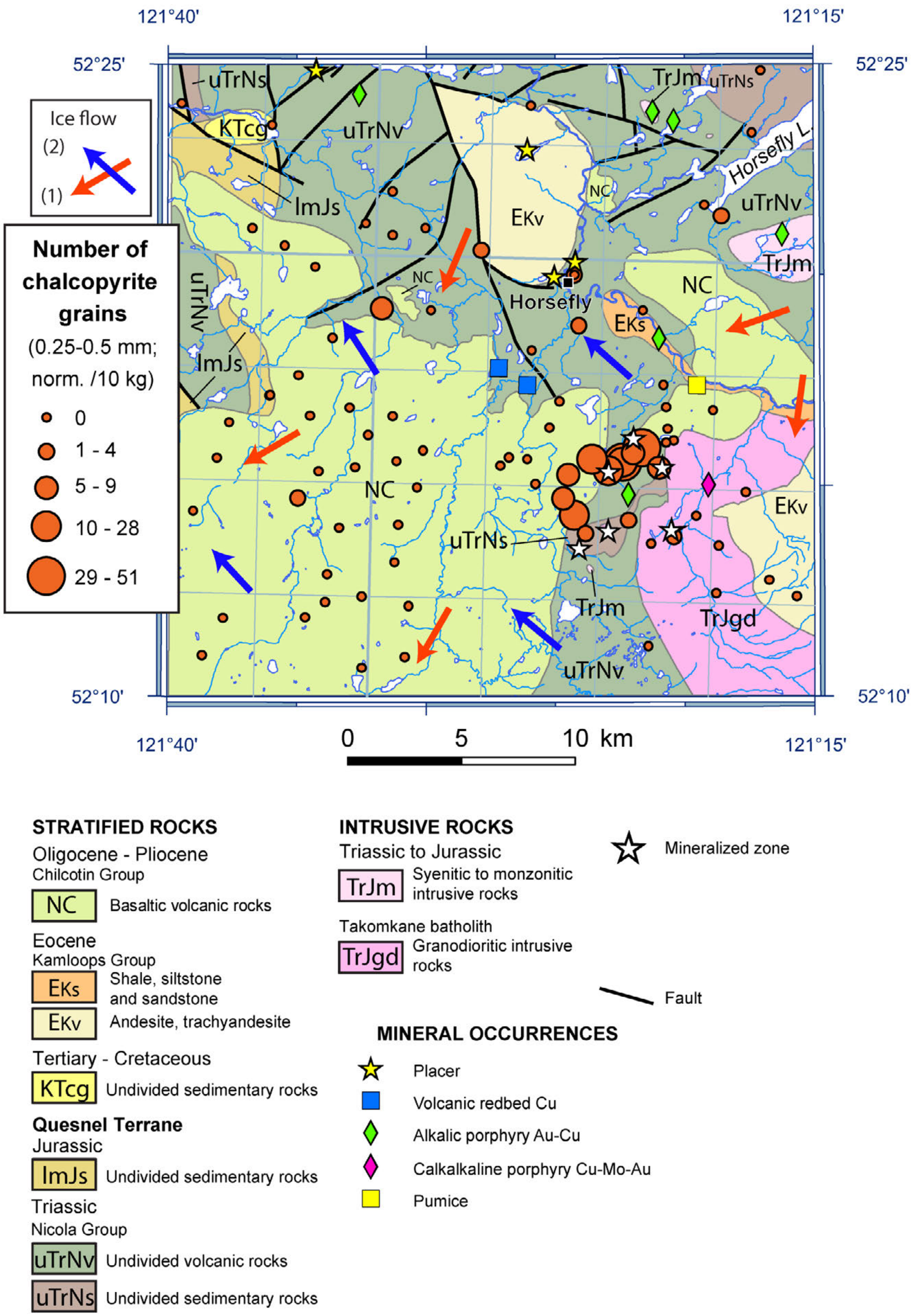

Figure 8 – Chalcopyrite grain counts in the 0.25-0.5 mm sized fraction and >3.2 s.g. density fraction of till normalized to 10 kg bulk sediment (<2 mm) at the Woodjam prospect. Bedrock geology simplified from Massey et al. (2005) and Logan et al. (2010).

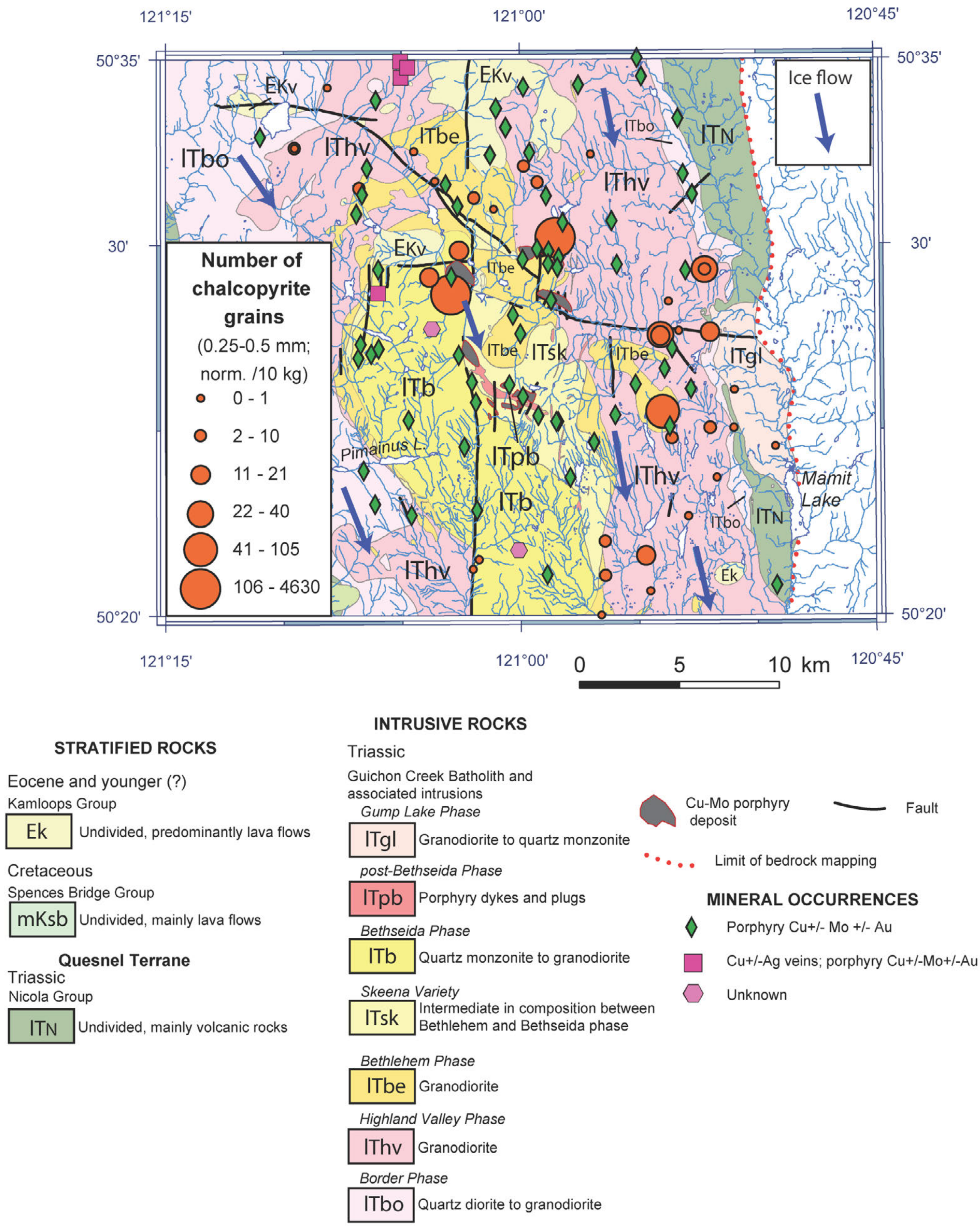

Figure 9 – Chalcopyrite grain counts in the 0.25-0.5 mm sized fraction and >3.2 s.g. density fraction of till normalized to 10 kg bulk sediment (<2 mm) at the Highland Valley Copper deposit. Bedrock geology simplified from McMillan et al. (2009).

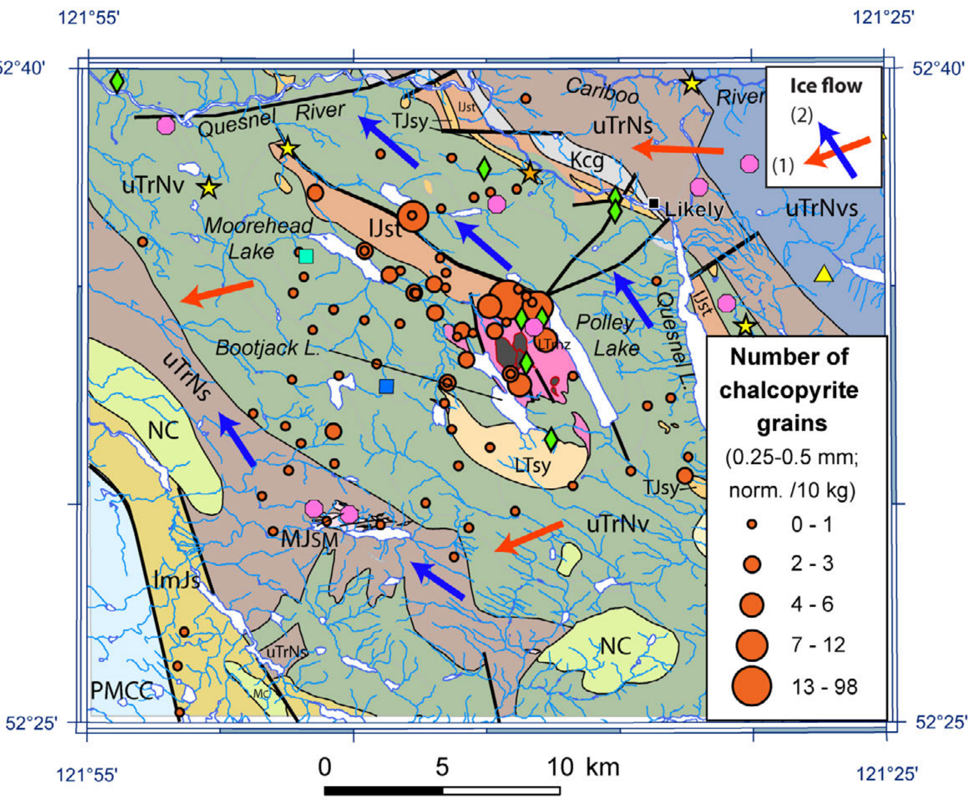

Figure 10 – Chalcopyrite grain counts in the 0.25-0.5 mm sized fraction and >3.2 s.g. density fraction of till normalized to 10 kg bulk sediment (<2 mm) at the Mount Polley deposit. Bedrock geology legend is the same as Figure 3.

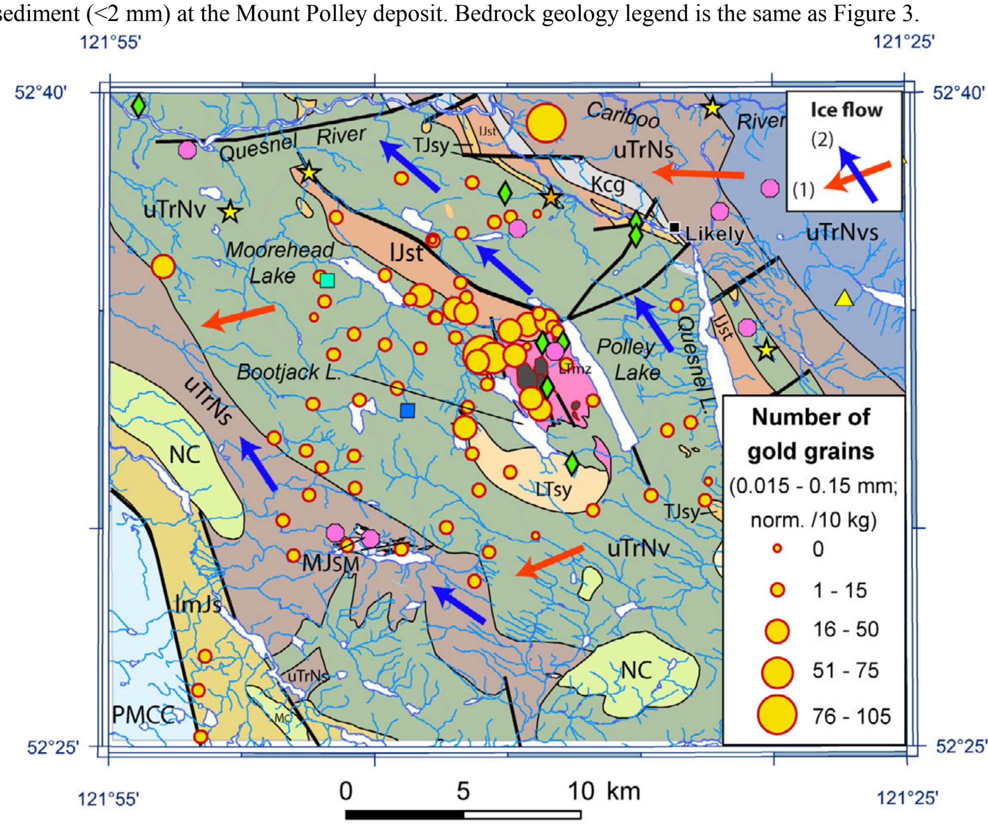

Figure 11 – Gold grain counts with long axis varying from 0.015 to 0.425 mm in the shaking table concentrates normalized to 10 kg bulk sediment (<2 mm) at the Mount Polley deposit. Bedrock geology legend is the same as Figure 3.

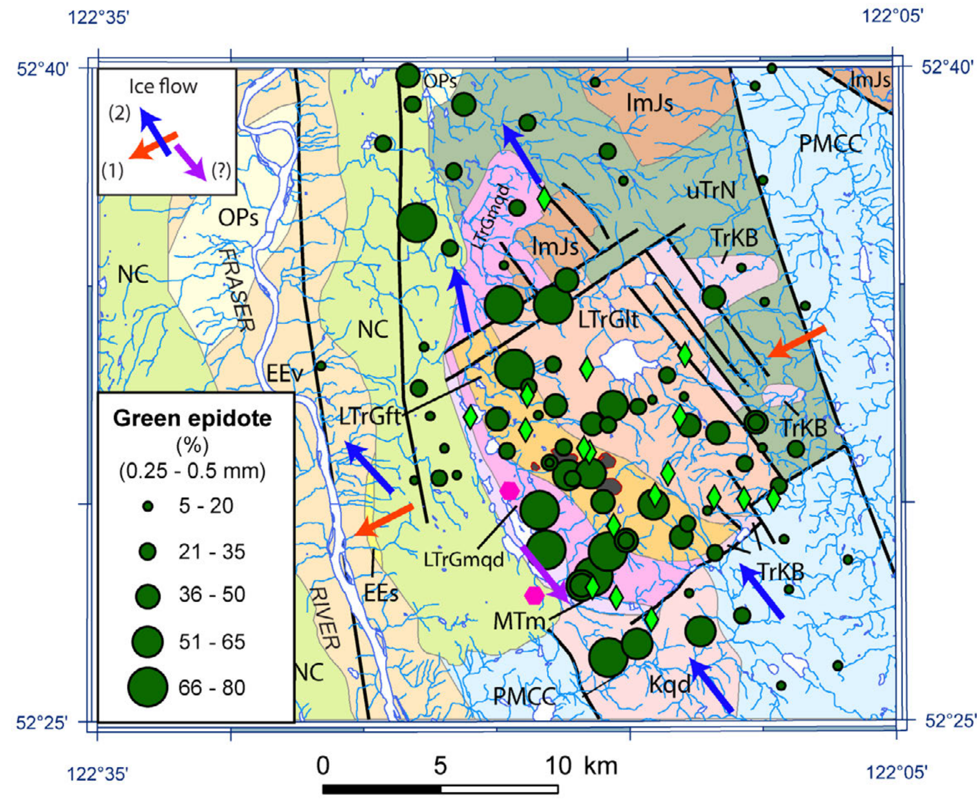

Figure 12 – Green epidote grain counts in the 0.25-0.5 mm sized fraction and >3.2 s.g. density fraction of till normalized to 10 kg bulk sediment (<2 mm) at the Gibraltar deposit. Bedrock geology legend is the same as Figure 4.

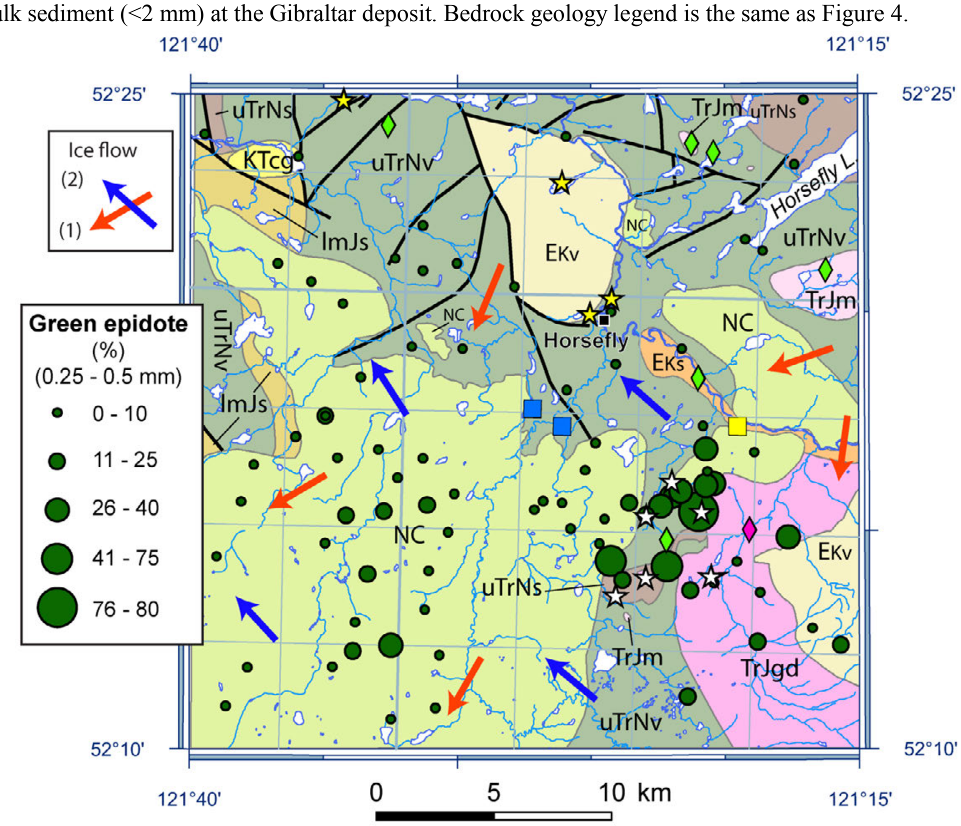

Figure 13 – Green epidote grain counts in the 0.25-0.5 mm sized fraction and >3.2 s.g. density fraction of till normalized to 10 kg bulk sediment (<2 mm) at the Woodjam prospect. Bedrock geology legend is the same as Figure 8.

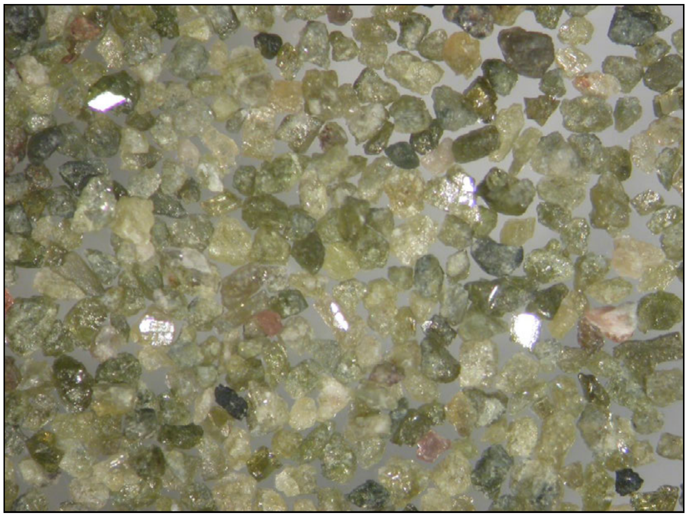

Figure 14 – Heavy mineral concentrates (0.25-0.5 mm; s.g. >3.2; paramagnetic fraction 0.8 – 1 A; see Figure 2B) from sample 11-PMA-017A-1 collected in the Woodjam area. The amount of epidote in this concentrate is estimated at 80 % (+/- 10 %). Field of view width: 5 mm. Modified from Plouffe et al. (2013a).

pared to the regional magnetite derived from non-mineralised sources. Grondahl (2014) and Piziak et al. (2015) found that the magnetite grains with a Ti and Sn content similar to the Mount Polley magnetite breccia (ca. 0.5 to ca. 3 ppm Sn and 1100-11,000 ppm Ti) can be detected in till up to 6 kilometres to the northwest (down-ice) from the deposit. Beyond this distance, the magnetite grains in till showed no overlapping composition with magnetite from the deposit.

Similar to the magnetite study at Mount Polley, Chapman et al. (2015, in press) studied the composition of tourmaline in till and bedrock at Woodjam to identify the signature of the porphyry mineralised bedrock source. Tourmaline major element compositions were determined by electron microprobe (EPMA) at the University of Ottawa MicroAnalysis Laboratory. Structural formulae were calculated by normalisation on 31 anions and by assuming that Y+Z+T = 15 atoms-per-formula-unit (apfu). Tourmaline from the Takom and Deerhorn zones at Woodjam has compositions typical of tourmaline associated with Cu-porphyry mineralisation as identified by Baksheev et al. (2012). Typically, Mg content is approximately two atoms-per-formula unit and individual analyses are distributed along the $FeAl_{-1}$ substitution vector in a Fe-Mg (apfu) bivariate plot, as well as along the magnesiofoitite-povondraite join in an Fe-Al-Mg ternary plot. The tourmaline abundance in till defines a wide dispersal train which extends approximately 10 km northwest (down-ice) from the Woodjam deposit and the Takomkane batholith (Chapman et al., in press). How-

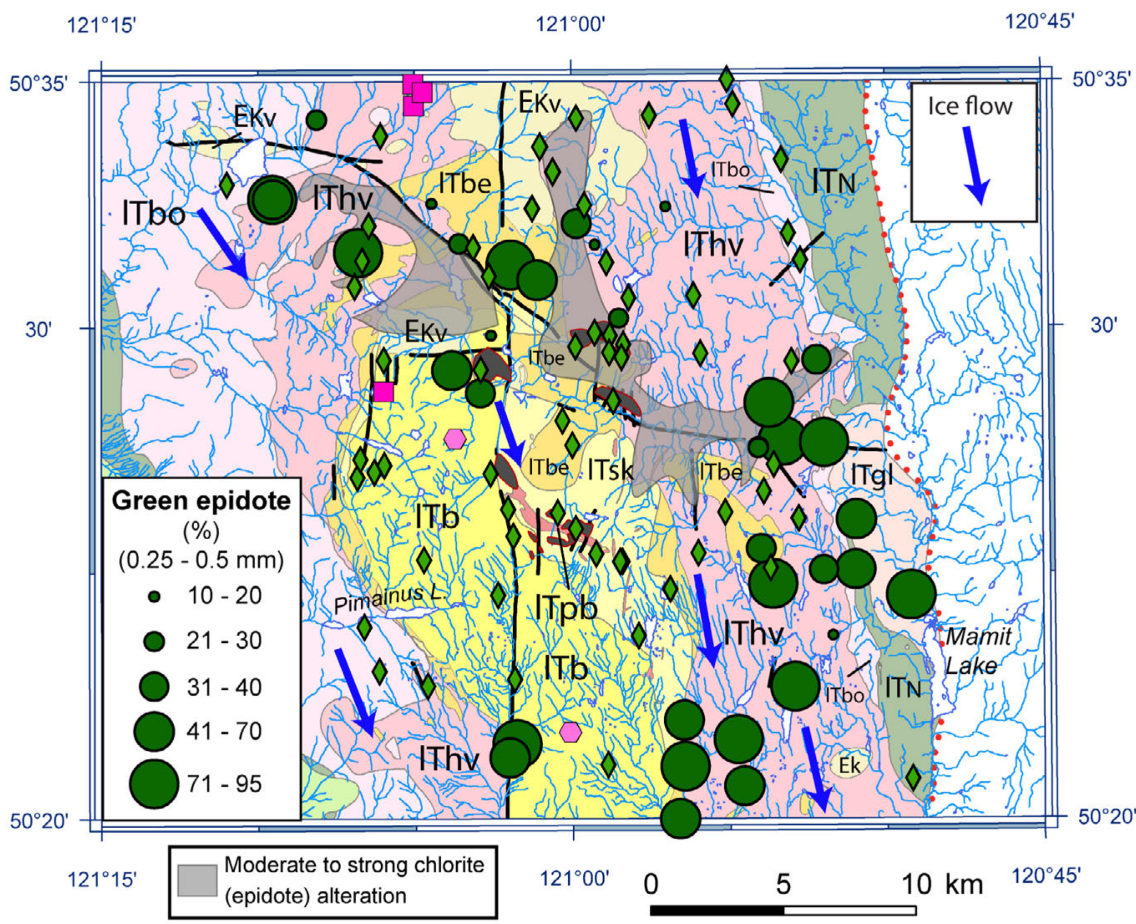

Figure 15 – Green epidote grain counts in the 0.25-0.5 mm sized fraction and >3.2 s.g. density fraction of till normalized to 10 kg bulk sediment (<2 mm) at the Highland Valley Copper deposit. Bedrock geology legend is the same as Figure 9. The mapped extent of chlorite (epidote) alteration is from Casselman et al. (1995).

ever, only tourmaline grains in a till sample located <1 km from Deerhorn have a composition similar to the one in the mineralised source (Chapman et al., in press).

Till indicators of Cu porphyry mineralisation identified as part of this study are used to identify potential exploration targets.

Our study indicates that elevated Cu concentrations along with the presence of chalcopyrite in till can be indicative of Cu porphyry mineralisation. In addition, the presence of elevated Au grain counts or elevated Au concentrations found in association with the Cu indicators could indicate the presence of Cu-Au porphyry mineralisation (Hasmi et al., in press a). Obviously, the interpretation of the till composition needs to take into account the geological setting which needs to be favourable for porphyry mineralisation. In the Quesnel terrane of the Cordillera, a favourable setting for porphyry mineralisation includes Late Triassic to Early Jurassic felsic to intermediate intrusions (McMillan, 1991; McMillan et al., 1991, 1995, 1996; McMillan and Panteleyev, 1995; Logan and Mihalynuk, 2014).

To test the geochemical and mineralogical indicators of Cu-Au porphyry mineralisation identified as part of this study, Plouffe and Ferbey (2015a) have revisited the regional till composition data obtained as part of the Mountain Pine Beetle Program of the Geological Survey of Canada (Plouffe et al., 2009, 2010) for a region which includes two Late Triassic – Early Jurassic intrusions within the Quesnel terrane: the Thuya and Takomkane batholiths. Two vectors of ice-flow movements have been identified in this region by Plouffe et al. (2011b) including a first movement to the west to southwest derived from the Cariboo Mountains which were the source of ice at the onset of the last glaciation. A second flow to the south to southeast originated from an ice divide which formed around the 52 degree latitude following the coalescence of ice from the Coast and Cariboo mountains (Fig. 16). Two regions with elevated Cu concentrations above 359 ppm in the clay-sized fraction of till are defined from this regional data set: one about 30 kilometres south of Woodjam, at the western limit of the Takomkane batholith but underlain by the Late Triassic Spout Lake pluton, and a second one at the northern limit of the Thuya batholith (Fig. 16). Within those two areas, the Au grain content of till is also elevated including numerous adjacent samples with more than 66 Au grains per 10 kg of bulk material (<2 mm) (Fig. 17). A total of 57 samples selected from within and outside the regions with elevated Au and Cu were processed for porphyry Cu indicator minerals identification as part of the Mountain Pine Beetle Program. All samples with more than 3 chalcopyrite grains per 10 kg are located at the northern limit of the Thuya batholith or at the western limit of the Takomkane batholith, above the Spout Lake pluton (Fig. 18). Based on the mineralogical and geochemical indicators of Cu-Au porphyry

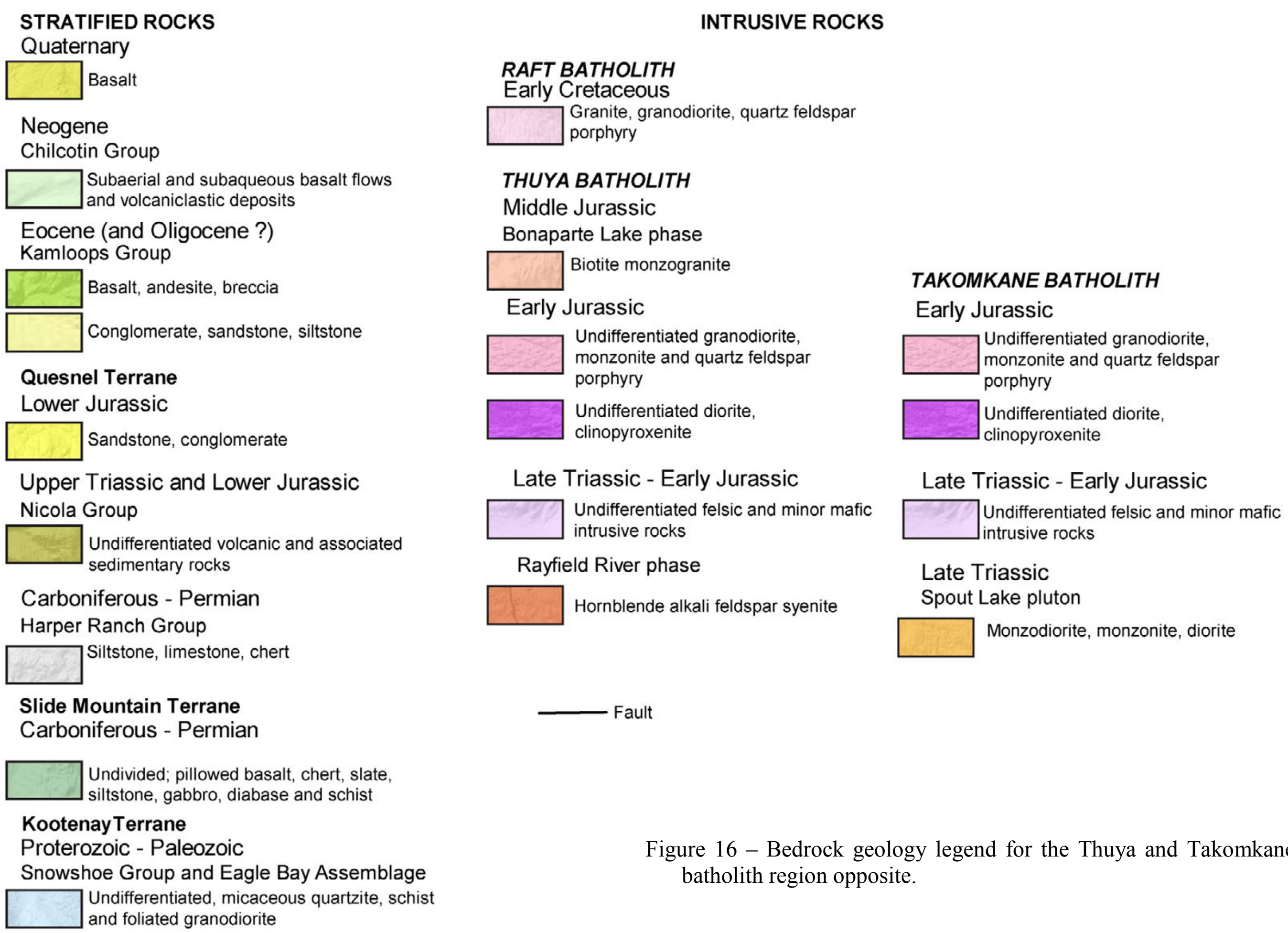

Figure 16 – Bedrock geology legend for the Thuya and Takomkane batholith region opposite.

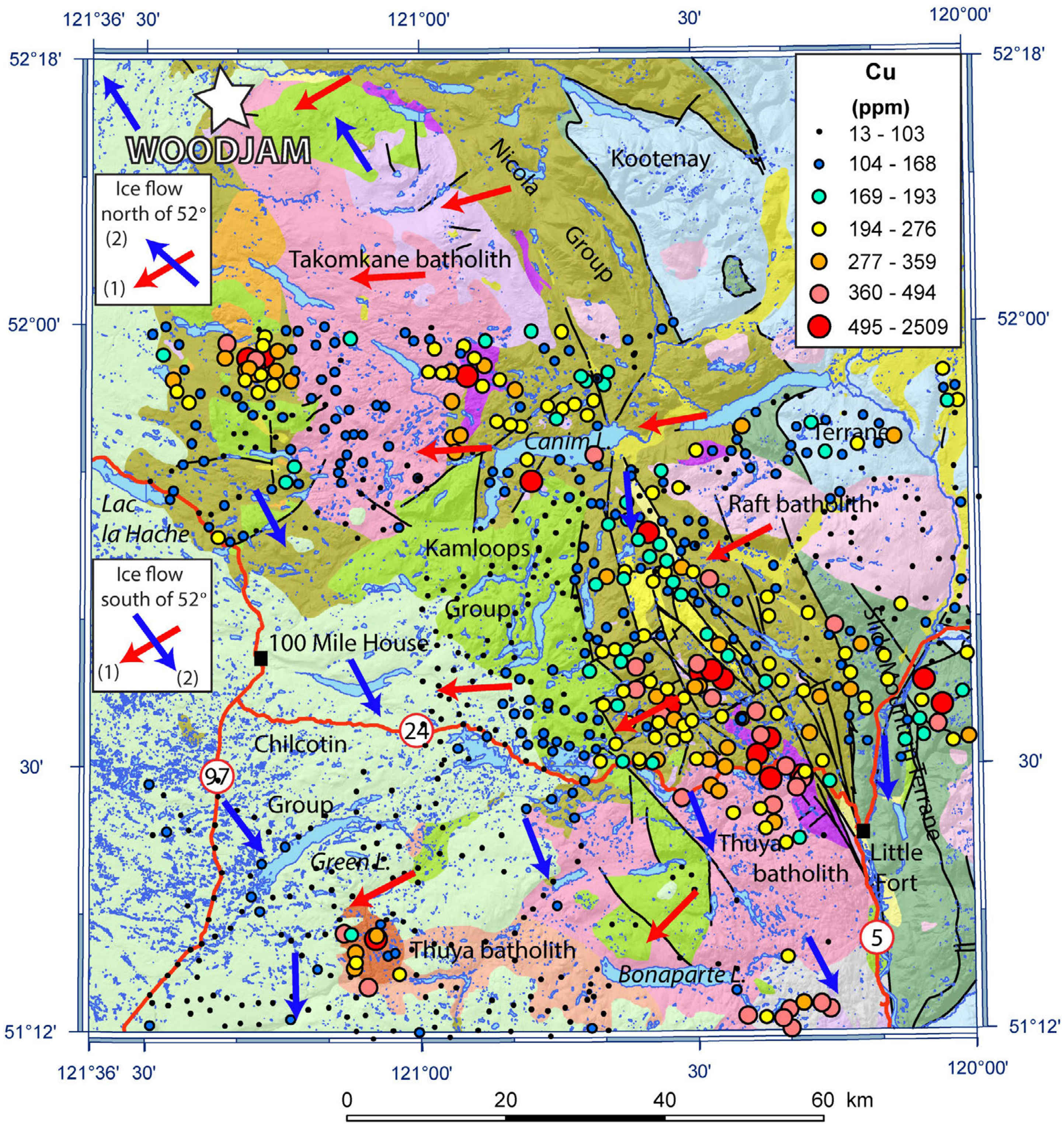

Figure 16 (cont.) – Copper in the clay-sized fraction of till in the region of the Thuya and Takomkane batholiths analysed by ICP-MS after an HCl:HNO3 leach (1:1) . The map includes the region of the Woodjam prospect. Data from Plouffe et al. (2010) and figure modified from Plouffe and Ferbey (2015a). Bedrock geology is simplified from Campbell and Tipper (1971), Schiarizza et al. (2002a, b), Schiarizza and Boulton (2006), Schiarizza and Bligh (2008), and Anderson et al. (2010). Also, it is based on the compilation presented in Plouffe et al. (2011b). Generalized ice flow from Plouffe et al. (2011b) and Ferbey et al. (2013). Note the ice divide around the 52 degree latitude.

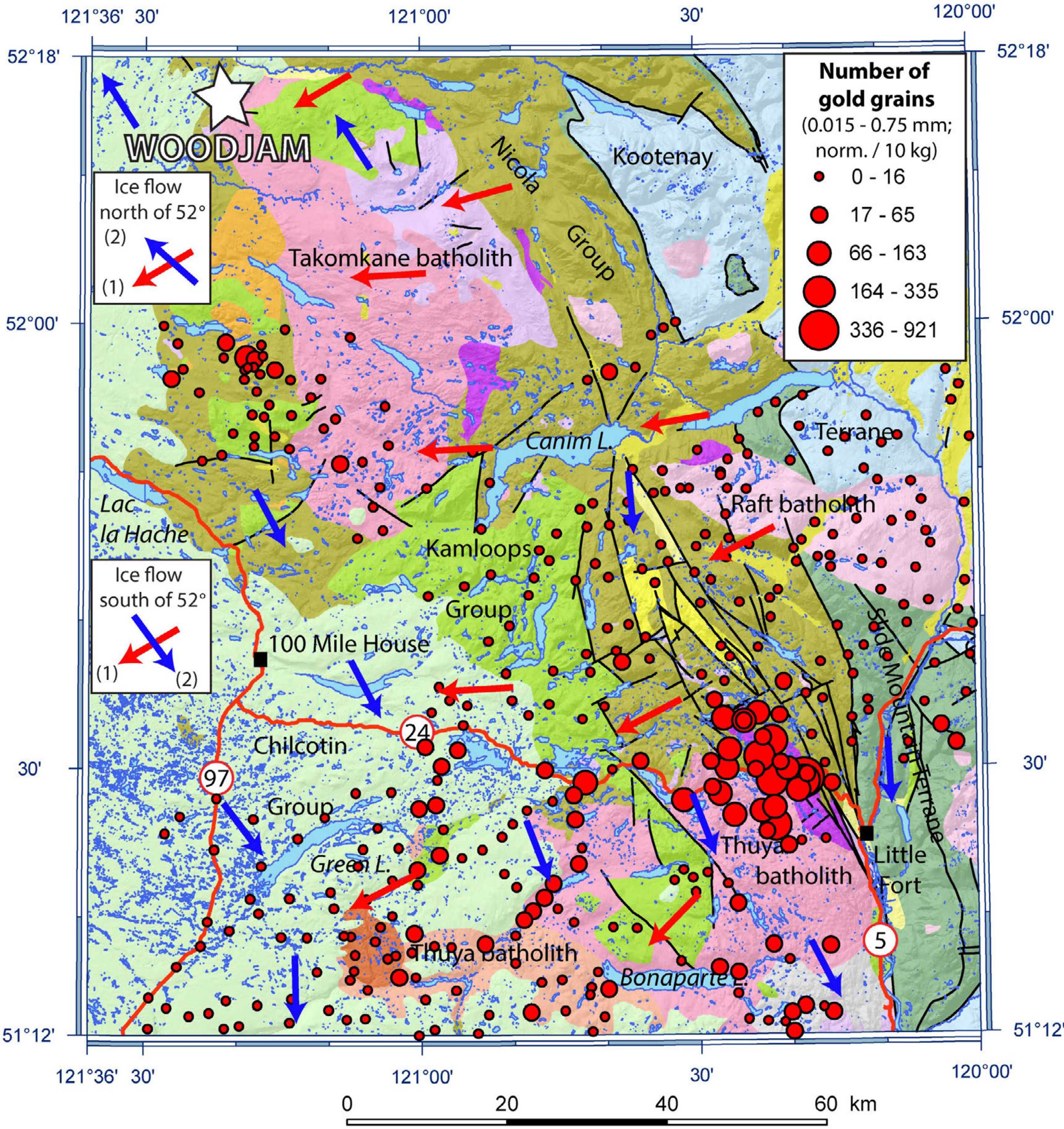

Figure 17 – Gold grain counts with long axis varying from 0.015 to 0.700 mm in the shaking table concentrates normalized to 10 kg bulk sediment (<2 mm) in the region of the Thuya and Takomkane batholiths. Bedrock geology legend is the same as Figure 16.

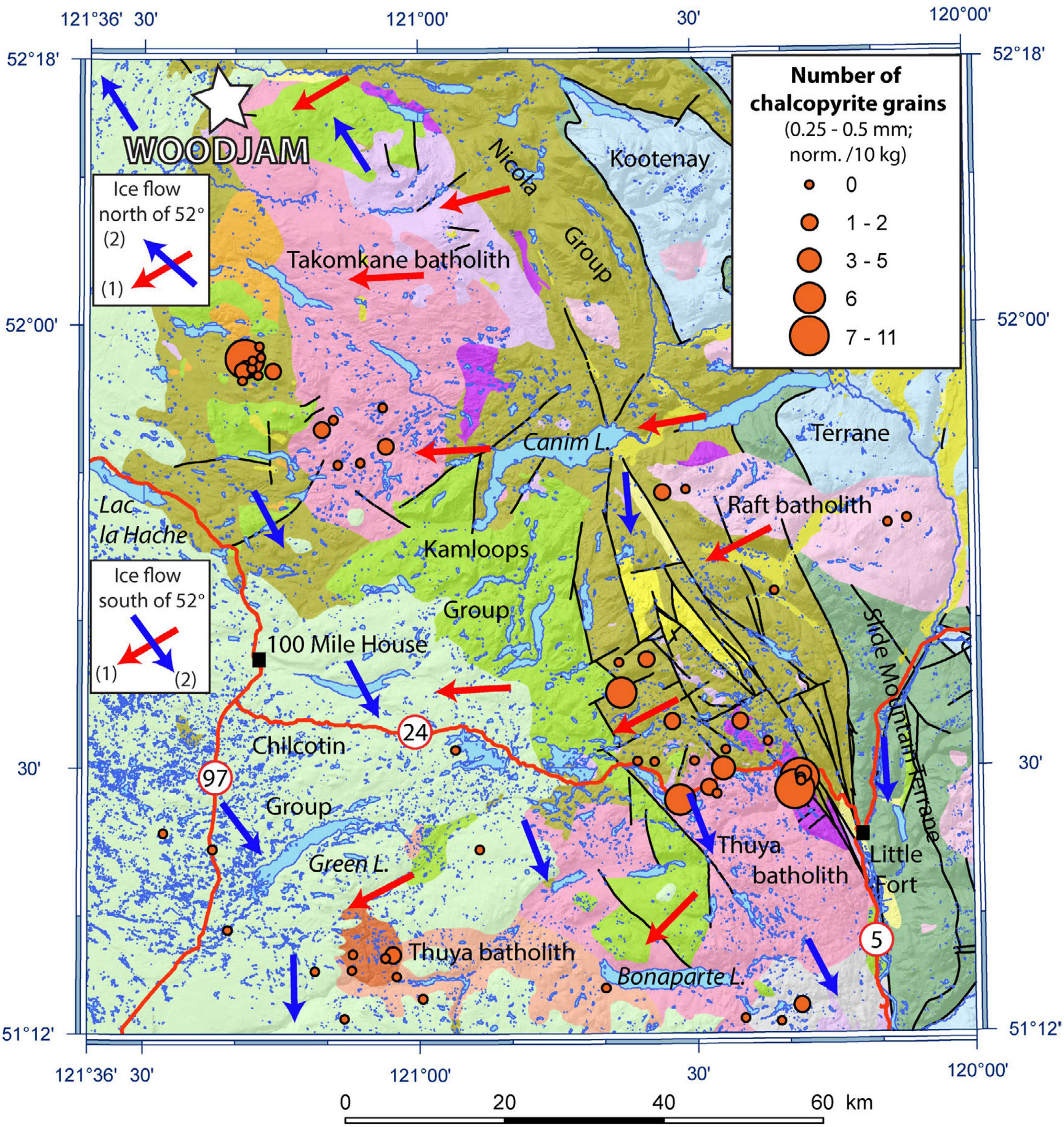

Figure 18 – Chalcopyrite grain counts in the 0.25-0.5 mm sized fraction and >3.2 s.g. density fraction of till normalized to 10 kg bulk sediment (<2 mm) in the region of the Thuya and Takomkane batholiths. Bedrock geology legend is the same as Figure 16..

mineralisation observed in till, we postulate that the northern sector of the Thuya batholith and the western margin of the Takomkane batholith have potential to host porphyry-style Cu-Au mineralisation.

Recommendations for mineral exploration for Cu porphyry mineralisation in glaciated landscape

From the results presented above, we demonstrate that till composition (geochemistry and mineralogy) can reflect the presence of Cu porphyry mineralisation which was exposed to glacial erosion. Geochemical and mineralogical anomalies identified in till can be traced to their bedrock source if the regional ice-flow history (detrital glacial transport direction) is taken into account. Depending on the available funds and the scope of a mineral exploration project (e.g., grass root exploration at a regional scale or detailed follow-up exploration at a property scale) different approaches are recommended.

At a regional scale, till geochemistry based on a sample spacing of one to two kilometres would have defined the presence of elevated concentrations for multiple metals in till at the four study sites (e.g., Cu, Mo, Au, Zn, Hg). In a scenario were there is limited exploration funding available, till geochemistry alone could be sufficient to identify high metal contents or anomalies that could be derived from, and thus indicators of, porphyry mineralisation. This approach would be practical in regions with a high potential for porphyry mineralisation such as the Quesnel and Stikine terranes. Processing all or a selected number of samples for indicator minerals is also recommended since till mineralogy provides additional key information on the mineralogy of the bedrock source. For example, at Mount Polley some till samples with background Au concentrations (<15 ppb in the silt and clay-sized fraction; <0.063 mm) also contained elevated numbers of gold grain (>15 grains per 10 kg) (Hasmi et al., in press a). Furthermore, in an hypothetical scenario where only the alteration zones of a fertile porphyry system were exposed to glacial erosion no high contents of commodity-metals would be detected in till. In this case, only the alteration minerals in the till would be indicative of the presence of buried porphyry mineralisation. Lastly, in a region of thick till such as Woodjam, the geochemical signal in till derived from mineralisation is diluted within a short distance down-ice from the mineralised bedrock source; only two samples located within one kilometre of the mineralisation returned elevated Cu concentrations (> 265 ppm) above concentrations observed in samples throughout the region (Fig. 19). On the other hand, at the same site, 10 samples contain greater than four chalcopyrite grains per 10 kg which is greater than the amounts observed in regional samples (0 to 4 chalcopyrite grains/10 kg; Fig. 8). Plus, samples with elevated chalcopyrite grain counts (> 4 grains / 10 kg) are located up to 3 km from known mineralised zones and define a mineralogical anomaly in till of about 6 by 3 km.

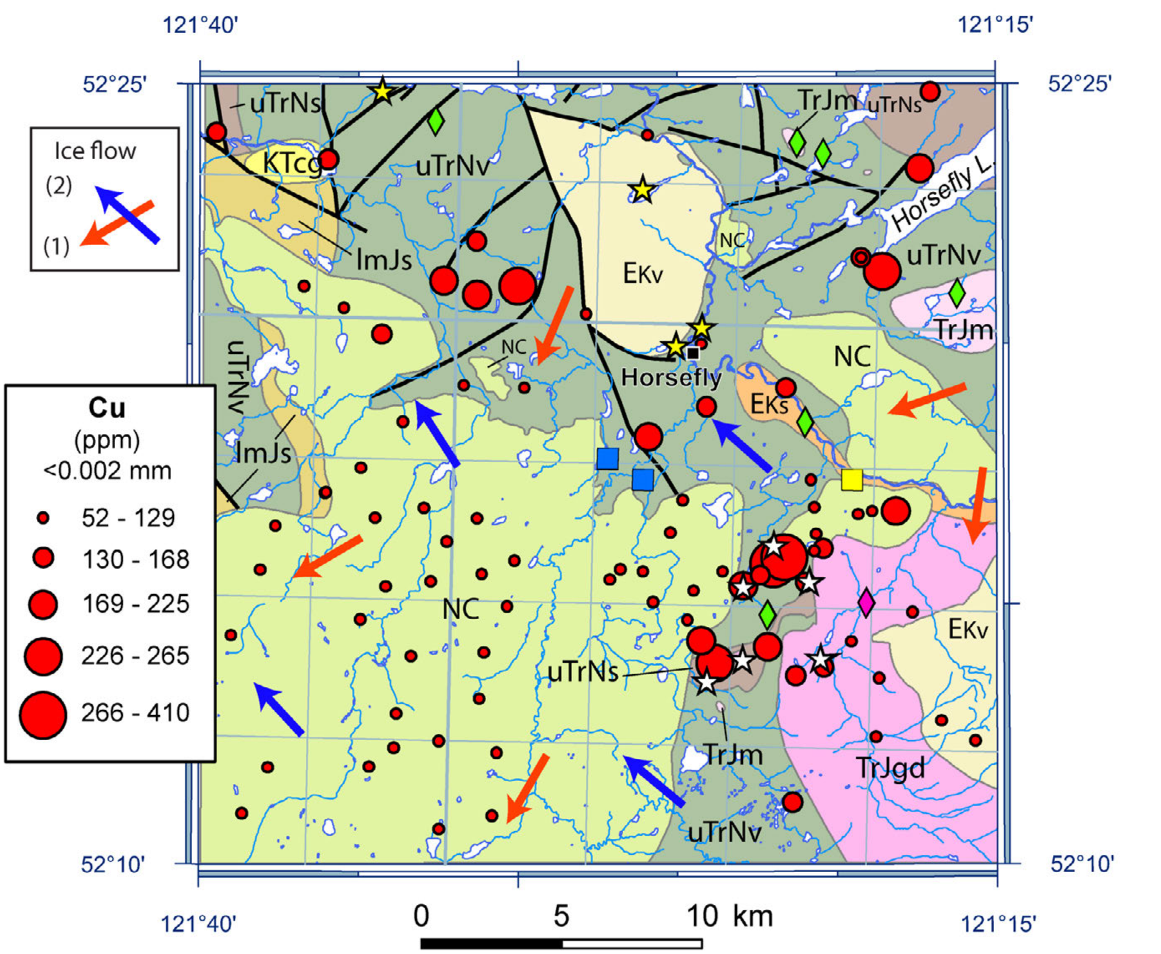

Figure 19 – Copper in the clay-sized fraction of till at the Woodjam prospect analysed by ICP-MS after an HCl : HNO_3 leach (1:1). Bedrock geology legend is the same as Figure 8.

The same approach (that is collecting till samples for geochemical and mineralogical analyses) is recommended at a property scale where the objective might be to locate a bedrock source for advanced exploration activity (e.g., drilling). In such a scenario, the spacing between till samples should be less than one kilometre. The orientation of the till sampling transect and the sample spacing need to take into account the potential shape of the bedrock source and ice-flow direction (e.g., Levson, 2001). Trenching and/or shallow drilling with light equipment might be required to facilitate the sampling of unweathered till at a depth greater than one metre or the sampling of till at various depth intervals if the till is thick (Plouffe, 1995; McMartin and McClenaghan, 2001).

Publications in progress

In addition to the references provided in the text above, a number of publications produced as part of this project have recently been published or are currently in progress. Surficial geology maps at 1:50,000 scale are being prepared for each study site. The surficial geology map for Mount Polley mine area is published (Hashmi et al., 2015) and the one for Highland Valley is in press (Plouffe and Ferbey, 2015b). Surficial geology maps for Gibraltar and Woodjam are in an advance stage of production (i.e., aerial photograph interpretation is completed and data is being prepared for the final map). An open file report with all data on till geochemistry and mineralogy along with all the quality assurance and quality control data is being prepared (A. Plouffe and T. Ferbey, work in progress, 2015). One overview paper on till geochemistry and mineralogy at the four study sites is nearly completed and will be submitted to a peer review scientific journal in 2015. One scientific paper on till geochemistry and mineralogy at Mount Polley is in press (Hasmi et al., in press a). This paper is part of the M.Sc. thesis of S. Hashmi at Simon Fraser University, under the supervision of B.C. Ward. The thesis includes a study of glacial dispersal from the Mount Polley deposit and the reconstructed glacial history of the region based on surficial geology mapping. A paper on glacial dispersal and till composition at the Gibraltar deposit and a second one for the Woodjam deposit are planned with first drafts expected to be completed in 2015.

Future research

Results from this project show how till geochemistry and mineralogy can be used to explore for Cu porphyry mineralisation buried by glacial sediments. As with other research, this work has generated related questions; the answers to which could only further the mineral exploration method. For instance, can the geochemical compositions of porphyry indicator minerals, or their internal textures, be indicative of the bedrock source lithology and the fertility of the ore system? That question was partly addressed by Bouzari et al. (2010, 2011a, b) who demonstrated that apatite derived from unaltered and unmineralised host rock at six porphyry deposits in British Columbia displays yellow to brown colors under cathodoluminescence compared to green and grey apatite in altered and mineralised rocks. The colour of the luminescence is controlled by the composition of apatite; lower Mn/Fe ratios in green apatite (mineralised source) compared to the yellow and brown apatite (unmineralised source). Chlorine, Na and S are also depleted in alteration apatite (Bouzari et al., 2011a).

Similarly, the composition of magnetite (Ti, V, Mn, Ca, Al), a common accessory mineral occurring in a variety of rock types, can serve to discriminate different deposit types (e.g., Dupuis and Beaudoin, 2011). As indicated above, Piziak et al. (2015) and Grondahl (2014) investigated the composition of magnetite in till and bedrock samples from Mount Polley, collected as part of this project. In another study of magnetite composition in porphyry deposits of British Columbia, Bouzari et al. (2011a) demonstrated that in a variety of altered host rocks of porphyry deposits, magnetite grains display a pink core that is replaced by hematite interpreted to reflect the increasing oxidation state of the porphyry system.

The composition of other alteration minerals associated with porphyry mineralisation also has the potential to be tied to bedrock type and fertility. For example, epidote recovered from propylitic alteration zones associated with porphyry and skarn deposits in the Baguio district, Republic of the Philippines, has a chemistry which varies with distance from the deposit centres (Cooke et al., 2014). In their study, epidote contains higher concentrations of Cu, Mo, Au and Sn near the central potassic alteration zone and pathfinder elements (As, Sb, Pb, Zn, Mn) are enriched in epidote up to 1.5 km from the deposit centre. Similarly, given that Cu-sulphides and accessory minerals in supergene zones of porphyry deposits have heavy Cu isotopic signatures (Zhu et al., 2000; Mathur et al., 2009, 2010), the Cu isotopic composition of those minerals recovered from transported sediments could be used to identify a supergene cap source.

This brief overview of recent compositional work conducted on porphyry indicator minerals reveals the great potential of developing exploration methods based on the petrography and chemical composition of a wide variety of alteration and ore minerals associated with porphyry systems. Most of these studies were conducted on minerals recovered from bedrock; the abundance and chemistry of the same minerals in transported glacial and non-glacial sediments needs to be assessed (see also Bouzari et al., 2011a). In other words, do these indicator minerals survive transport in glacial and non-glacial environments and are they present in sufficient amounts in the till to be detected? How extensive is their footprint in the transported medium? The development of indicator minerals for mineral exploration in glaciated and drift covered area should continue for porphyry-style mineralisation but also for other mineral deposit types. The development of new exploration methods in glaciated areas is increasingly important given the increasing demand for a variety of metals and non-metals on global markets and the known difficulty associated to their search in drift covered areas.

Conclusion

Results from the till orientation surveys conducted near four Cu porphyry deposits in British Columbia demonstrate that till geochemistry and mineralogy can detect Cu porphyry mineralisation that was exposed to glacial erosion and is now covered by glacial sediments. The porphyry mineralisation is reflected by the high concentrations of commodity metals (e.g., Cu, Mo, Au), pathfinder elements (e.g., Zn, Ag, Hg), ore minerals (e.g., chalcopyrite, gold grains) and alteration minerals (e.g., epidote, andradite garnet, apatite) in till. These elements and minerals can be dispersed over several kilometres from their bedrock source in the down-ice direction. Resulting dispersal trains have different shapes and lengths which are influenced by transport vectors (i.e., multiple ice-flow events) and in some cases multiple bedrock sources (e.g., cluster of sub-economic mineralised zones peripheral to the zones of economic mineralisation). Future research should include detailed studies on the physical and chemical characteristics of porphyry Cu indicator minerals that are diagnostic of a Cu porphyry source and its potential fertility. The development of mineral exploration methods using the geochemical and mineralogical composition of transported sediments should not be limited to porphyry deposits but should include other mineral deposit types.

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