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**GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8038**

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GEOFILE 2016-10**

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porphyry deposits in British Columbia**

A. Plouffe and T. Ferbey

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2016

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

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Abstract

Till sampling surveys were completed in 2011, 2012 and 2013 in the region of four Cu-porphyry mineralized zones in British Columbia: Highland Valley Copper Mine (Cu-Mo porphyry), Gibraltar Mine (Cu-Mo porphyry), Mount Polley Mine (Cu-Au porphyry), and the Woodjam prospect (Cu-Au-Mo porphyry). The goal of these till sampling surveys is to develop new mineral exploration methods using till geochemistry and mineralogy to detect buried porphyry mineralization. This Open File contains the geochemical, mineralogical and grain size (textural) data produced as part of this activity. Implemented quality control and quality assurance measures demonstrate that analytical results are fit for geological interpretation and are not affected by analytical artefact or sampling.

Introduction

The next generation of mines discovered in Canada are unlikely to be exposed at surface. The current trend in mineral exploration is to look for mineralization at increasing depth and decreasing grades (McIntosh, 2010). To address this issue, the Geological Survey of Canada (GSC) launched the five year Targeted Geoscience Initiative-4 (TGI-4) Program (2010-2015) with the goal of developing geoscience to support enhanced effectiveness of deep exploration. Within the context of the Canadian Cordillera, “deep” can be defined as any mineralization which is not exposed at surface and is covered by unconsolidated glacial sediments or Tertiary volcanic bedrock.

One objective of the TGI-4 till sampling survey in British Columbia is to develop new exploration methods using till geochemistry and mineralogy for the search of Cu porphyry mineralization concealed by glacial deposits (Anderson et al., 2012a, b; Ferbey et al., 2014). To accomplish this, till orientation surveys were conducted at four study sites: Highland Valley Copper Mine (Cu-Mo porphyry), Gibraltar Mine (Cu-Mo porphyry), Mount Polley Mine (Cu-Au porphyry), and the Woodjam prospect (Cu-Au-Mo porphyry) (Fig. 1). This Open File includes geochemistry, mineralogy and textural data for a total of 310 till samples collected in 2011, 2012 and 2013.

Geological Setting

A brief overview of the geological setting of the four study sites is presented below. All four of the Cu-porphyry deposits tested occur in Late Triassic to Early Jurassic intrusions within the Quesnel Terrane, an island arc assemblage of upper Paleozoic and lower Mesozoic volcanic, sedimentary and intrusive rocks (Fig. 1). [Note: At the scale of Figure 1, Gibraltar deposit appears in the Cache Creek Terrane. However, a more detailed geological map (Fig. 2) shows that the deposit is in the Quesnel Terrane]. Late Triassic to Early Jurassic intrusions within the Quesnel Terrane are known to be highly prospective for Cu-porphyry mineralization (Logan and Mihalynuk, 2014).

All four study sites are located within the Interior Plateau of British Columbia (Holland, 1976) which is a region of subdued topography with isolated mountain ranges. Glacial sediments cover the vast majority of the Interior Plateau. Bedrock exposures are generally limited.

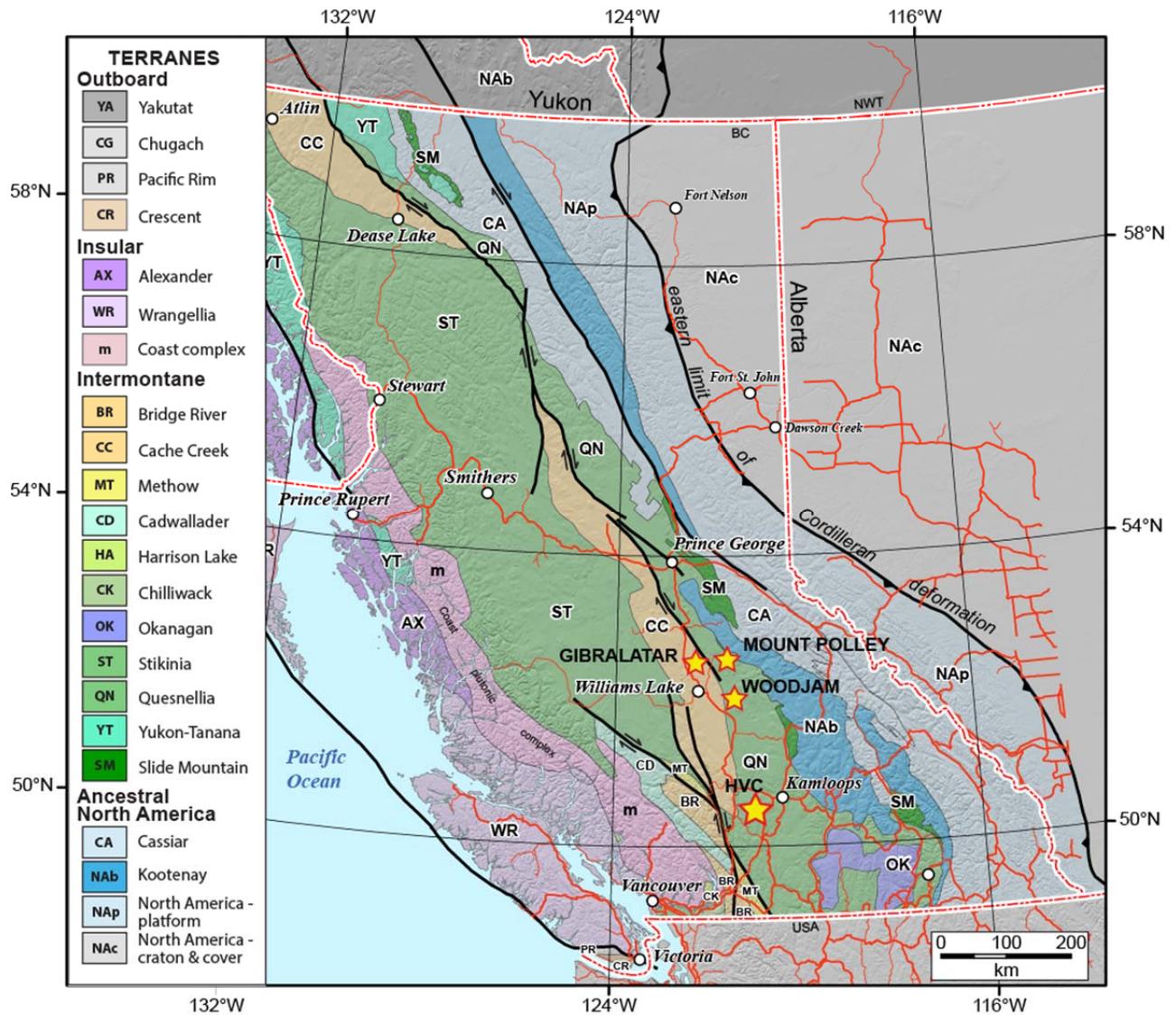
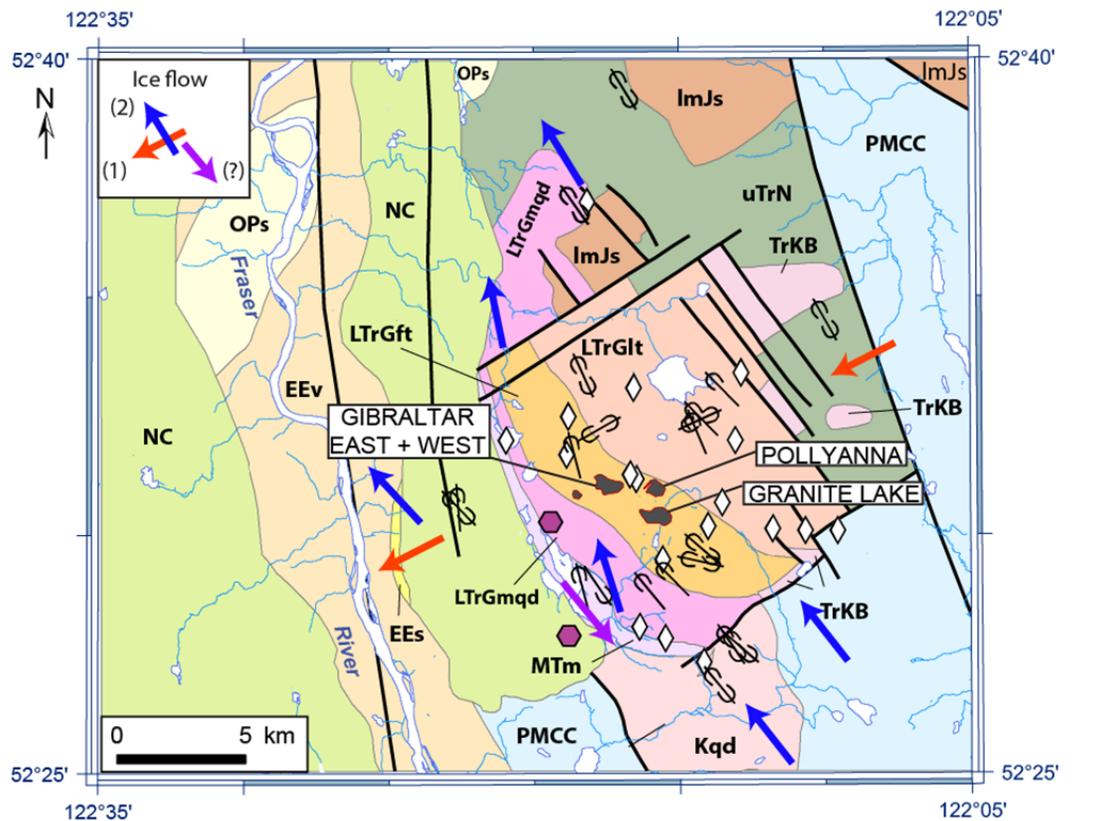


Figure 1. Location map of the four study sites (yellow star) in British Columbia; modified from Plouffe and Ferbey (2015a). Study sites are depicted as yellow stars on the terrane map of Colpron and Nelson (2011). HVC – Highland Valley Copper deposits.

Gibraltar Mine

Gibraltar Mine, located 65 km north of Williams Lake, British Columbia, is a calc-alkaline Cu-Mo porphyry deposit hosted in the Late Triassic Granite Mountain batholith which intrudes the volcanoclastic rocks of the Nicola Group (Schiarizza, 2014) (Fig. 2). A more detailed account of the geology and mineralization of the Gibraltar deposit is presented in Drummond et al. (1973, 1976), Sutherland Brown (1974), Bysouth et al. (1995), Ash et al. (1999a, b), Ash and Riveros (2001), van



STRATIFIED ROCKS

Neogene

Chilcotin Group

NC Basaltic volcanic rocks with lesser sedimentary rocks

Oligocene to Pliocene

OPs Conglomerate

Eocene to Oligocene

Endako Group

EEv Basaltic volcanic rocks with lesser sedimentary rocks

EEs Sedimentary rocks

Quesnel Terrane

Lower - Middle Jurassic
Ashcroft Formation

ImJs Polymictic volcanic and plutonic-clast conglomerate

Upper Triassic and Lower Jurassic
Nicola Group

uTrN Volcanic sandstone-siltstone

Cache Creek Terrane

Carboniferous - Lower Jurassic
Cache Creek Complex

PMCC Undivided marine sedimentary and volcanic rocks

METAMORPHIC ROCKS

Eocene ?

MTm Chlorite-sericite-quartz-feldspar schist

INTRUSIVE ROCKS

Triassic? Jurassic? Cretaceous?

Burgess Creek stock (Border phase)

TrKB Quartz diorite, tonalite

Middle Cretaceous

Sheridan stock (ca. 108 Ma)

Kqd Quartz diorite, quartz monzonite, granodiorite, granite

Late Triassic

Granite Mountain Batholith (ca. 215 Ma)

LTrGmtd Melanocratic quartz diorite

LTrGft Foliated tonalite (Mine phase)

LTrGlt Leucocratic tonalite, trondhjemite (Granite Mountain phase)

POLLYANNA

Cu-Mo porphyry deposit

Fault

Glacial striations (paleo ice-flow direction known, unknown)

MINERAL OCCURRENCES

◇ Porphyry Cu +/- Mo +/- Au

● Cu-Mo setting unknown

Figure 2. Bedrock geology map of the Gibraltar mine region with regional ice-flow directions. Bedrock geology simplified from Ash et al. (1999b), Massey et al. (2005) and Schiarizza (2014). Generalized ice-flow movements from Plouffe and Ferbey (2015b)

Straaten et al. (2013), and Schiarizza (2014). Rotherham et al. (1972) present an overview of mineral exploration at the time of the mine opening. They indicate that prior to mining, bedrock exposure was less than 5% in the area of economic mineralization; the vast majority of the mineralization was concealed by glacial sediments.

The mine has been in operation from 1972 to present, but was on care and maintenance status for a brief period from 1998 to 2004 (Liles, 2005; van Straaten et al., 2013). Combining past production and current resources (2013) Gibraltar Mine represents a 1.22 billion tonnes deposit with a Cu grade of 0.317% and an estimated Mo grade of 0.010% (van Straaten et al., 2013). Major sulphide minerals include chalcopyrite and pyrite with lesser amount of molybdenite and sphalerite.

A till orientation survey was completed in the region of the Gibraltar Mine as part of the Mountain Pine Beetle project of the GSC (Plouffe et al. 2011a).

Mount Polley Mine

Mount Polley Mine is an alkalic Cu-Au porphyry deposit located 8 km southwest of Likely, British Columbia. It is hosted within the Late Triassic Mount Polley intrusive complex which intrudes metasedimentary and volcanic-arc assemblages of the Upper Triassic Nicola Group (Fig. 3). The regional geology, deposit geology, mineralization and alteration at Mount Polley have been described by Hodgson et al. (1976), Fraser et al. (1993, 1995), Fraser (1994), Logan and Mihalynuk (2005), Logan et al. (2007a, b), Tosdal et al. (2008), Rees (2013), and Rees et al. (2013, 2014). A detailed study on the mineralogical zonation and isotope geochemistry of the Northeast Zone was recently completed by Pass (2010) and Pass et al. (2014).

The mine has been in operation since 1997 with an interruption period from 2001 to 2005. To date, 80 million tonnes of ore have been milled producing 452 million pounds of Cu, 695 000 ounces of Au, and 2.2 million ounces of Ag (Rees, 2013). In 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). Chalcopyrite and bornite are the major Cu ore minerals at Mount Polley. Gold is found as inclusions 0.005 to 0.040 mm in size in chalcopyrite (Fraser et al. 1995).

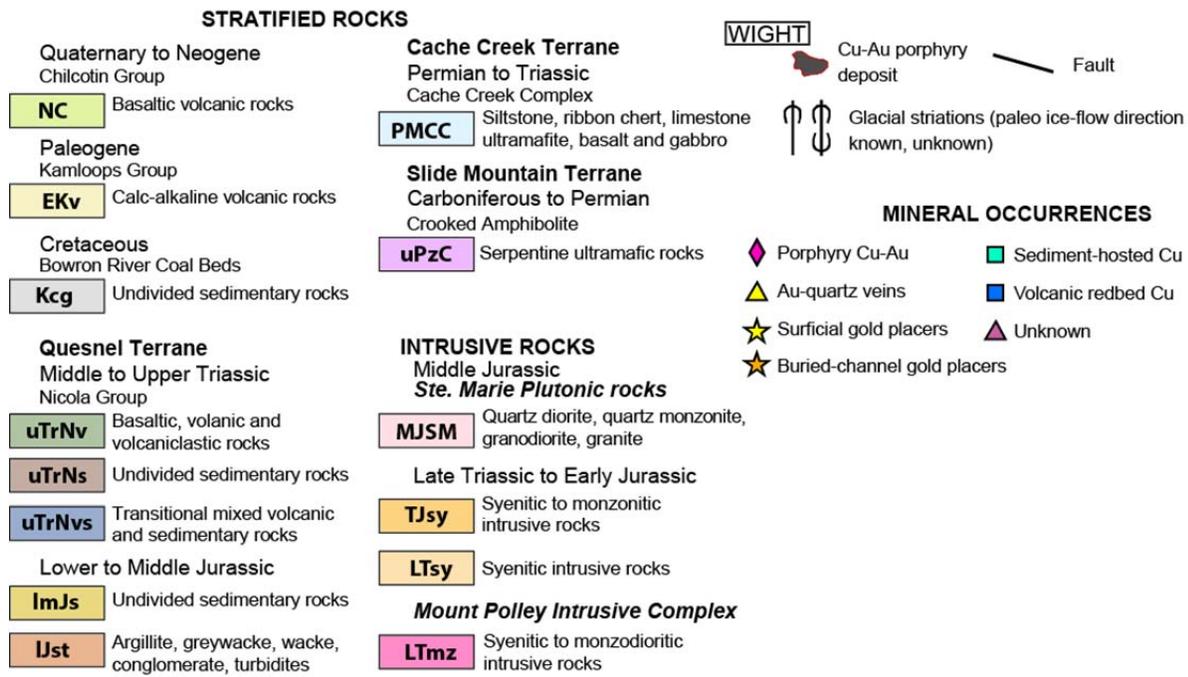
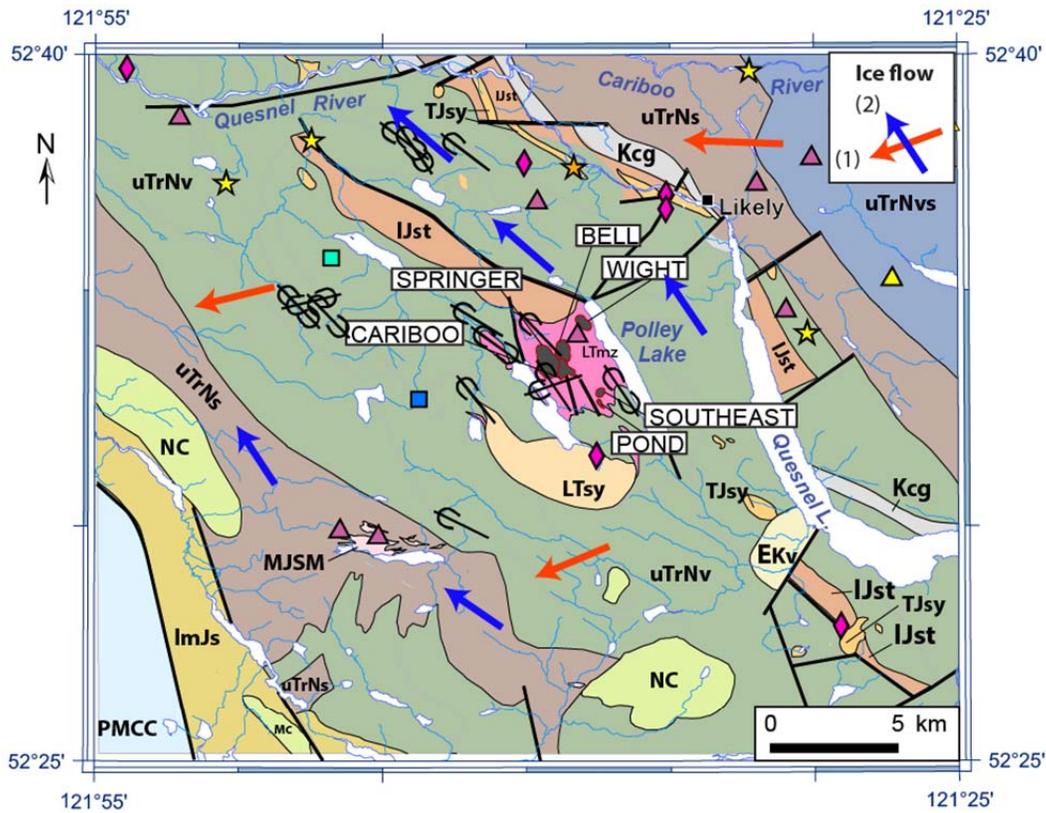


Figure 3. Bedrock geology map of the Mount Polley mine region with regional ice-flow directions. Bedrock geology simplified from Massey et al. (2005), Logan et al. (2007a, 2010), and Rees et al. (2014). Generalized ice-flow movements from Hashmi et al. (2015a)

Woodjam prospect

The Woodjam prospect, located 45 km east of the city of Williams Lake, British Columbia, is at the northern limit of the Early Jurassic calc-alkaline, monzodiorite to quartz monzonite Takomkane Batholith (Schroeter, 2009) (Fig. 4). The batholith intrudes the Nicola Group volcanic and associated sedimentary rocks (Schiarizza et al., 2009b). For the Woodjam prospect, the regional geological setting is provided by Schiarizza et al. (2009a, b), the age constraints on mineralization by Logan et al. (2011), and the descriptions of alteration by del Real et al. (2013) and Vanderkerkove et al. (2014). Geophysical surveys and drilling have defined six Cu-Au-Mo porphyry type mineralized zones: Deerhorn, Megabuck, Spellbound, Southeast, Takom, and Three Firs. The Deerhorn, Megabuck, Takom, Three Firs, and Spellbound zones occur within the contact zones of satellite intrusion located up to 1.5 km north of the main batholith as oppose to the Southeast zone which is within the main batholith (Anderson et al., 2012b). Vanderkerkove et al. (2014) suggest that the Woodjam district hosts calc-alkalic Cu-Au±Mo porphyry mineralization.

No mineral reserves have been determined for the Woodjam prospect. However, the inferred resources from the three most advanced projects at Woodjam (Southeast, Deerhorn and Takom zones) are evaluated at 269 million tonnes with 0.22 to 0.31% Cu and 0.26 to 0.49 g/t Au (Sherlock et al., 2013; Sherlock and Trueman, 2013). The main ore minerals include pyrite, chalcopyrite, molybdenite, and minor bornite.

Previous geochemistry orientation surveys utilizing soil and plants were completed at the Woodjam prospect with the objective of developing new methods for detecting porphyry mineralization covered by Tertiary volcanic rocks and glacial sediments (Bissig et al., 2013; Heberlein et al., 2013).

Highland Valley Copper Mine

The Highland Valley Copper Mine is located 54 km southwest of Kamloops, British Columbia. The porphyry Cu-Mo mineralization is hosted within the Late Triassic Guichon Creek batholith which intruded volcanic and sedimentary rocks of the Upper Triassic Nicola Group (Fig. 5). Economic mineralisation is distributed in five deposits: Valley, Lornex, Bethlemen, Highmont and JA. Details on the regional geology, mineralization and alteration at Highland Valley are presented in Bergey et al. (1971), McMillan (1985), Casselman et al. (1995), McMillan et al. (2009) and Byrne et al. (2013).

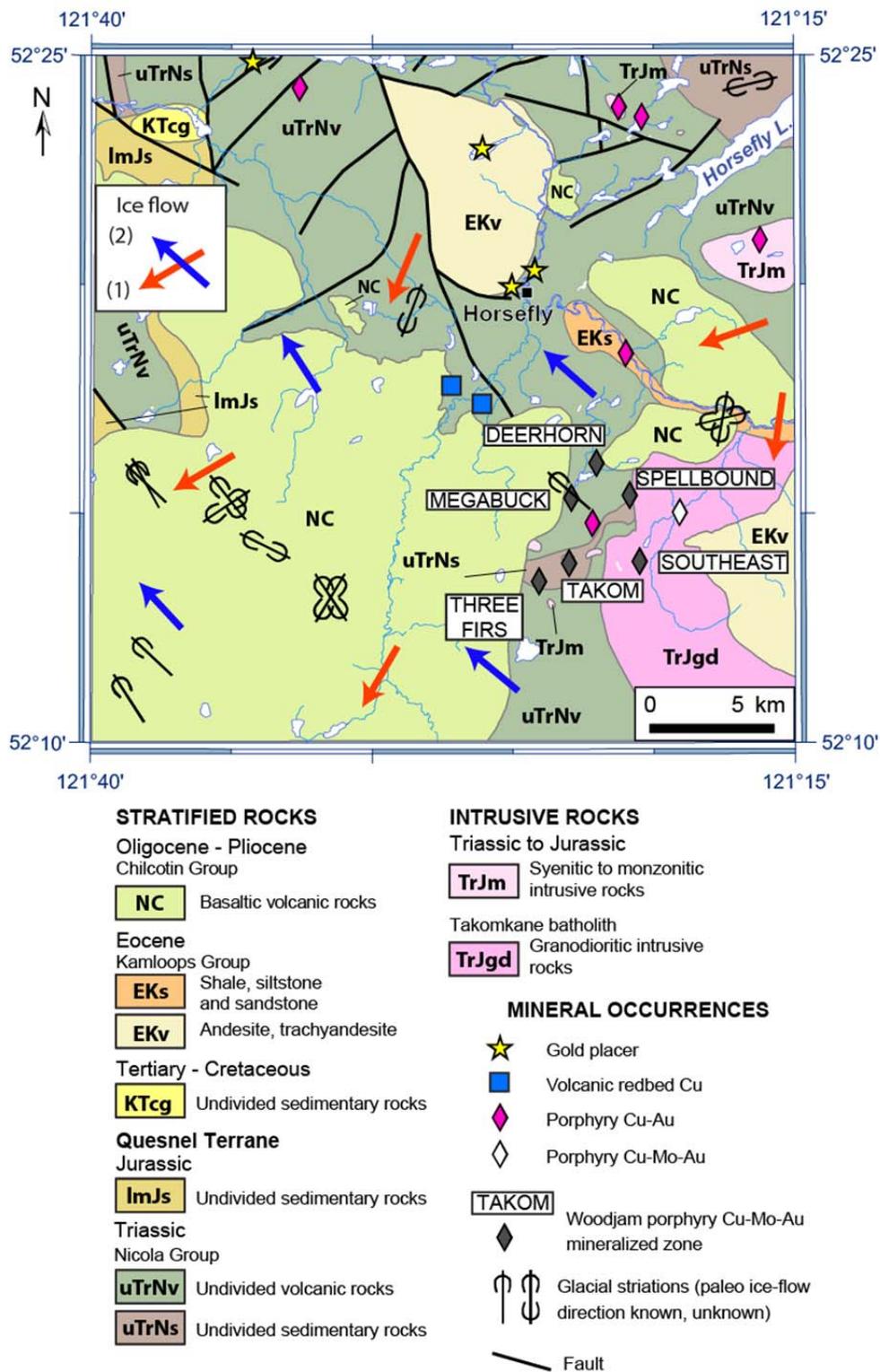


Figure 4. Bedrock geology map of the Woodjam prospect region with regional ice-flow directions. Bedrock geology simplified from Massey et al. (2005) and Logan et al. (2007a). Generalized ice-flow movements derived Ferbey et al. (2016)

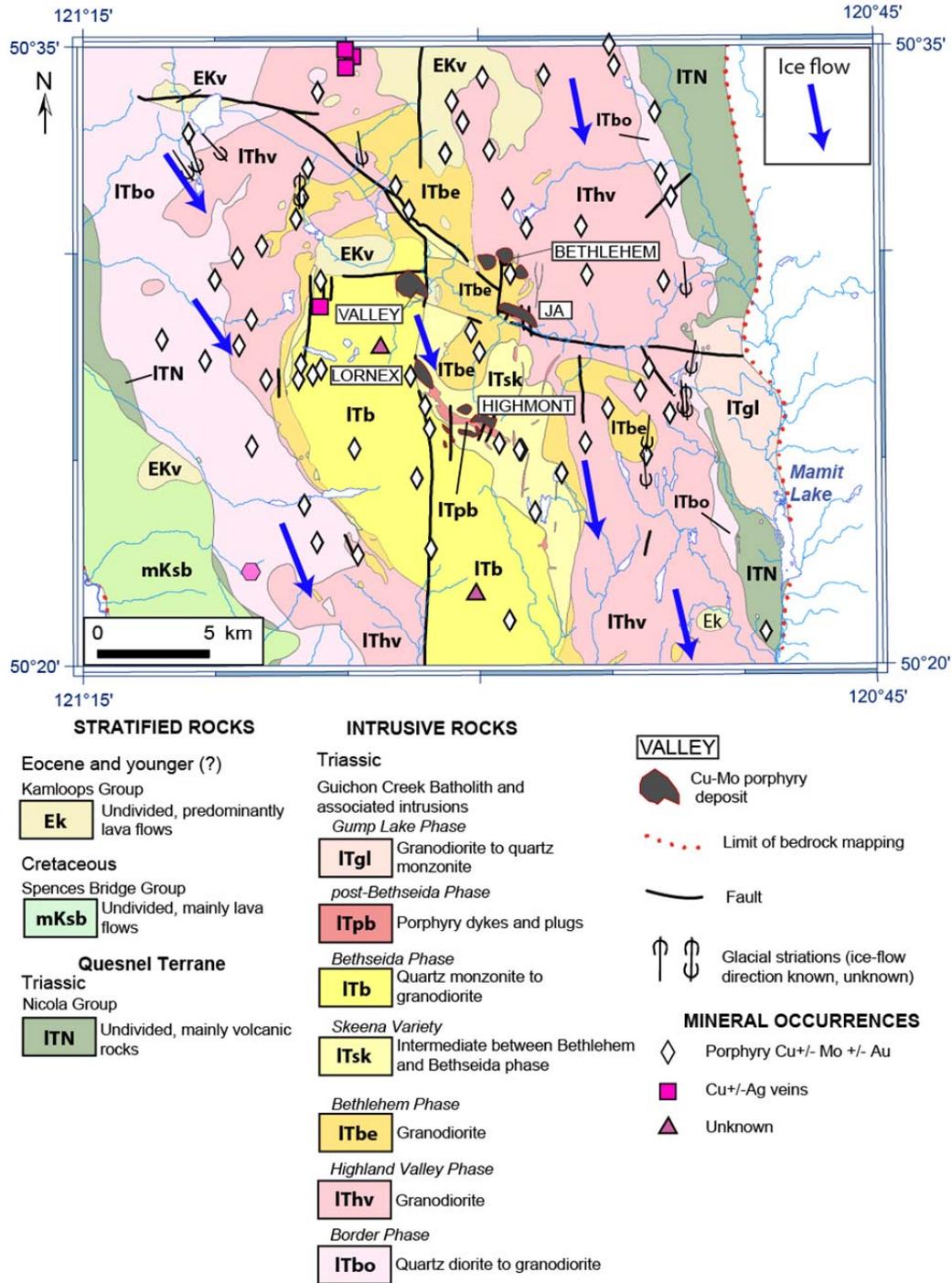


Figure 5. Bedrock geology map of the Highland Valley Copper mine region with regional ice-flow directions. Bedrock geology simplified from McMillan et al. (2009). Generalized ice-flow movements from Plouffe and Ferbey (2015c).

The mine has been in continuous operation since 1962 and as of December 2013 has processed 1615.16 million tonnes of ore grading 0.40% Cu and 0.010% Mo (Byrne et al., 2013). In December

2012, the reserves were estimated at 697 million tonnes at 0.29 % Cu and 0.008% Mo (Byrne et al., 2013). The main ore minerals include chalcopyrite, bornite, and molybdenite (Casselman et al., 1995). A description of the stratigraphy of overlying unconsolidated sediments exposed in the Valley Pit is presented in Bobrowsky et al. (1993).

Ice-flow history and glacial transport

Interpretation of till composition data presented in this report must be done in the context of the ice-flow history. In other words, till samples with elevated geochemical or mineralogical values can only be traced back to their bedrock source with knowledge of glacial transport vectors which are the product of ice-flow movements.

To reconstruct the ice-flow history at each study site, ice-flow indicators were measured at all scales. Drumlins, flutings, and crag-and-tails were mapped on aerial photographs and reported on surficial geology maps while striations, grooves and mini crag-and-tails (rat tails) were measured on bedrock outcrops with a compass (Hashmi et al., 2015a; Plouffe and Ferbey, 2015b, c; Ferbey et al., 2016) (Fig.6). At a few localities, two sets of glacial striations were observed indicating ice-flow movements diverging by more than 10°. In some cases age chronology between two sets could be established based on at least one of the following two criteria: 1) grooves of one set are cross cut by striations of a younger movement and (Fig. 6D), 2) striations and grooves of one set are only found in the lee (protected side) of an outcrop striated by a younger movement. Digital data on paleo ice-flow indicators are included with the surficial geology maps produced as part of this project: Hashmi et al. (2015a), Plouffe and Ferbey (2015b, c), and Ferbey et al. (2016).

The following glacial history for the four study sites has been developed by integrating the known regional glacial history (cf. Tipper, 1971a, b; Fulton, 1975; Clague, 1989; Ryder et al., 1991; Lian et al., 1999; Lian and Hicock, 2000; Plouffe et al., 2011c; Ferbey et al., 2013) with additional detailed measurements made as part of our study. At the onset of the Late Wisconsinan glaciation (Fraser Glaciation), valley glaciers advanced from two principal source regions: the Coast Mountains to the west and Cariboo Mountains to the east (Tipper, 1971a, b). During this early phase of glaciation, ice advanced west to southwest out of the Cariboo Mountains over the Mount Polley and Woodjam regions. At this time, glaciers also formed over isolated mountain ranges within the Interior Plateau (Clague, 1989; Plouffe, 2000). For instance, ice likely formed in the unnamed mountain range marked

with fresh cirques and arêtes 15 km north of Gibraltar (Plouffe and Ferbey, 2015b). Glaciers from this local ice source reached at least the Gibraltar deposit region as indicated by the presence of south-



Figure 6. Ice-flow indicators measured on outcrops: (A) striations on a granodiorite outcrop approximately 10 km northwest of the Highland Valley mine; no clear sense of ice movement on the outcrop hence the double arrow striation ($190^{\circ} - 010^{\circ}$); Brunton compass for scale is 22 cm; (B) rat-tail (mini crag-and-tail; outline with a dash line) on a chlorite-sericite-quartz schist approximately 4 km southwest of Gibraltar mine indicating an ice movement towards 145° ; knife is 24 cm long (C) rat-tail (mini crag-and-tail) on bedrock of the Mount Polley intrusive complex approximately one kilometer northwest of Mount Polley mine indicating an ice movement towards 315° ; knife is 24 cm long; (D) cross-cutting striations in the Woodjam prospect region on Chilcotin basalt; a first set of striations and grooves oriented $055-235^{\circ}$ is cross-cut by a second set at $125-305^{\circ}$; the age relationship is given by the presence of striations of the second set in the grooves of the first set; no sense of ice movement on this horizontal outcrop hence the double arrows on both sets of striations.

-southeastward directed rat tails measured on one outcrop located 3.5 km south of the deposit (Plouffe and Ferbey, 2015b). Glaciers from the Cariboo Mountains finally reached the Gibraltar region and advanced in a general southwestward direction. During this early stage, ice was thin and therefore, glacier movements were controlled by topography. As glaciation intensified, glaciers from the Coasts and Cariboo Mountains coalesced to form the southern sector of the Cordilleran Ice Sheet with an east-west ice divide located around 52° north latitude. Ice flowed towards the north and south from the divide. At the last glacial maximum, ice flowed independently of topographic elements and its direction was dictated by ice-surface slope.

Consequently, at Woodjam and Mount Polley there were two vectors of glacial transport that prevailed during the last glaciation: early west to southwest flow and later north to northwest flow. The same two ice movements occurred at Gibraltar but were preceded by an earlier ice flow to the southeast. Therefore, mineralized debris in till in these regions has been transported by any combination of up to three ice-flow movements. Two vectors of ice-flow movements can result in the formation of palimpsest dispersal trains like the ones identified at Mount Polley (Hashmi et al., 2015b) and in the region of the Bonaparte Lake map area, approximately 70 km south of the Woodjam prospect (Plouffe et al., 2011b, c). The three vectors of ice-flow movements, with diverging directions, in the Gibraltar Mine region produced irregular pattern of glacial dispersal (Plouffe et al., 2013a; Plouffe and Ferbey, 2015d) similar to amoeboid dispersal originally described by Shilts (1993) and more recently by Trommelen et al. (2013) amongst others, in regions with multiple diverging ice-flow movements. Amoeboid dispersal trains are a form of palimpsest dispersal which results from multiple cycles of glacial erosion and deposition with varying directions of ice movements.

In the Highland Valley Copper mine region, a single phase of ice flow to the south has been identified (Fulton, 1975; Ryder, 1976; Bobrowsky et al., 1993, 2002; Plouffe et al., 2013a, c; Plouffe and Ferbey, 2015c). At the last glacial maximum, the southward ice movement in this region is attributed to flow from the ice divide located near 52° north latitude. Local fluctuations in ice movement to the southeast and southwest are likely related to periods of time when the Cordilleran Ice Sheet was thin (e.g., pre and post-glacial maximum) with ice-flow patterns influenced by topography. Consequently, glacial dispersal with a single phase of glacial transport is expected in the Highland Valley district. For example, dispersal trains reflecting a single phase of ice flow have been reported from the Galaxy property (porphyry copper-gold) approximately 45 km east-northeast of Highland Valley (Kerr et al., 1993; Lett, 2011).

Field methods: till sampling

Field work was completed over a three year period including two weeks in the fall of 2011, four weeks in spring 2012, and two weeks in spring 2013. Field work predominantly consisted of sampling till, measuring ice-flow direction indicators at the outcrop scale and making observations for the production of a 1:50 000 scale surficial geology map for each study site (Hashmi et al., 2015a; Plouffe and Ferbey, 2015b, c; Ferbey et al., 2016). A total of 310 till samples (excluding duplicate samples) were collected from 290 sites following general procedures outlined in Spirito et al. (2011) and McClenaghan et al. (2013) as well as the protocols for the sampling of glacial sediment for indicator mineral analyses outlined in Plouffe et al. (2013c). At a limited number of sites with high till exposures, samples were collected at different depths. Most samples were collected from till exposures in road side cuts and ditches. Sample pits were dug from surface in rare instances. Samples were collected at an average depth of 80 to 100 cm (Fig. 7). Sample locations were recorded with a global positioning system (GPS) receiver integrated with a personal digital assistant (PDA). Field notes were captured at each site with the Ganfeld software running on the PDA (Shimamura et al., 2008). A complete set of the digital field notes, including sample description, is included with the surficial geology maps published as part of this project (Hashmi et al., 2015a; Plouffe and Ferbey, 2015b, c; Ferbey et al., 2016). Two samples were collected at each site. The large sample (9 to 15 kg) was taken for indicator mineral processing and the small one (1 to 2 kg) for geochemical analyses (see details below).

Appendix 1 contains basic sample information recorded in the field including: depth of sampling, sample type, 1:50 000 scale NTS map sheet, coordinates (NAD 83 UTM easting, northing; latitude and longitude). The depth of sampling, in centimeters, is recorded as an interval from the top (depth top) to the bottom (depth bottom) representing the sampled interval (e.g. from a depth of 75 to 90 cm), measured downwards from the ground surface. Sampling sites at each study site are shown in Figure 8.



Figure 7. Example of a sampling site (13-PMA-521) with large (ca. 10 kg) and small (ca. 2 kg) samples; measuring stick is 2 m long. Sample was taken from the bottom of the hole.

Laboratory methods

Geochemical analyses

Geochemical analyses were completed on the clay- (<0.002 mm) and the silt plus clay-sized (<0.063 mm) fractions from the small till samples (1 to 2 kg; Fig. 9). The grain-size separations were completed at the Sedimentology Laboratory of the GSC. Prior to completing the grain-size separations, an archive split of about 800 g was taken from each sample. The silt plus clay-sized fraction was separated by dry sieving, and the clay fraction by centrifuge and decantation following procedures outlined in Girard et al. (2004). Both size fractions were submitted for the following analytical procedures at a commercial laboratory (ACME Analytical Laboratories, Bureau Veritas Company, Vancouver, British Columbia): 1) 0.2 g aliquots were digested with lithium metaborate/tetraborate ($\text{LiBO}_2/\text{Li}_2\text{B}_4\text{O}_7$), fused at 980°C , dissolved in 5% HNO_3 and then analyzed by inductively coupled plasma emission spectrometry and mass spectrometry (ICP-ES and ICP-MS); 2) 0.5 g of clay and 30 g of silt plus clay aliquots were diluted in a hydrochloric (HCl) and nitric (HNO_3) acid solution (ratio 1:1, modified aqua regia) and analyzed by ICP-MS; 3) 0.1 g aliquot were ignited at

>1650°C in a Leco analyzer for total carbon and sulphur determination; and, 4) loss on ignition (LOI) was determined on 1 g aliquots by weight difference after ignition at 1000°C. Large silt plus clay aliquots (30g) were submitted for gold 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. Unmodified analytical reports received from ACME, including the detection limits, are presented in Appendices 2A (2011), 2B (2012) and 2C (2013) for the clay-sized fraction and in Appendix 3A (2011), 3B (2012), and 3C (2013) for the silt plus clay-sized fraction in a Microsoft Excel 2011 format (.xlsx). Each file contains a worksheet entitled “QA_QC_listing” with the list of field duplicates, laboratory duplicates, and standard samples (see below for details).

Indicator mineral processing and identification

The large till samples (9 to 15 kg) were sent for indicator mineral separation and identification at a commercial laboratory (Overburden Drilling Management Ltd., Nepean Ontario; ODM). Samples were completely processed and no archive split were taken. Heavy mineral concentrates were produced following the protocol adopted at the GSC (Plouffe et al., 2013c) using a two-step procedure including a shaking table and a heavy liquid (Fig. 10). Samples were first wet sieved to <2 mm and pre-concentrated on a shaking table. Clasts in the > 2mm fraction were rudimentarily classified and their amount estimated into four broad classes (volcanics/sediments, granitics, limestone/carbonates, and others). Heavy mineral concentrates obtained from the shaking table were panned in a small container (micro panning) and observed under a binocular microscope to determine the number of gold grains and their size. Averill (1988) estimates that on average 80% of the grains larger than 0.001 mm are recovered in this procedure; this size represents the smallest gold particles visible under the binocular microscope. Based on morphology, gold grains were classified as reshaped, modified or pristine as defined by DiLabio (1990). ODM estimates the gold concentration (calculated ppb) in the heavy mineral concentrates based on the number of gold grains, their size, and the total weight of the concentrate following a calculation outline in Averill and Zimmerman (1986) and Averill (1988). The shaking table concentrates were separated into mid- (>2.8-3.2 specific gravity - SG) and high-density (>3.2 SG) fractions using methylene iodide as a heavy liquid diluted with acetone to the correct SG. Magnetic minerals were removed from both fractions with a hand magnet. Both non-ferromagnetic density fractions were sieved to 0.25-0.5 mm, 0.5-1 mm and 1-2 mm fractions. Only the 0.25-0.5 mm

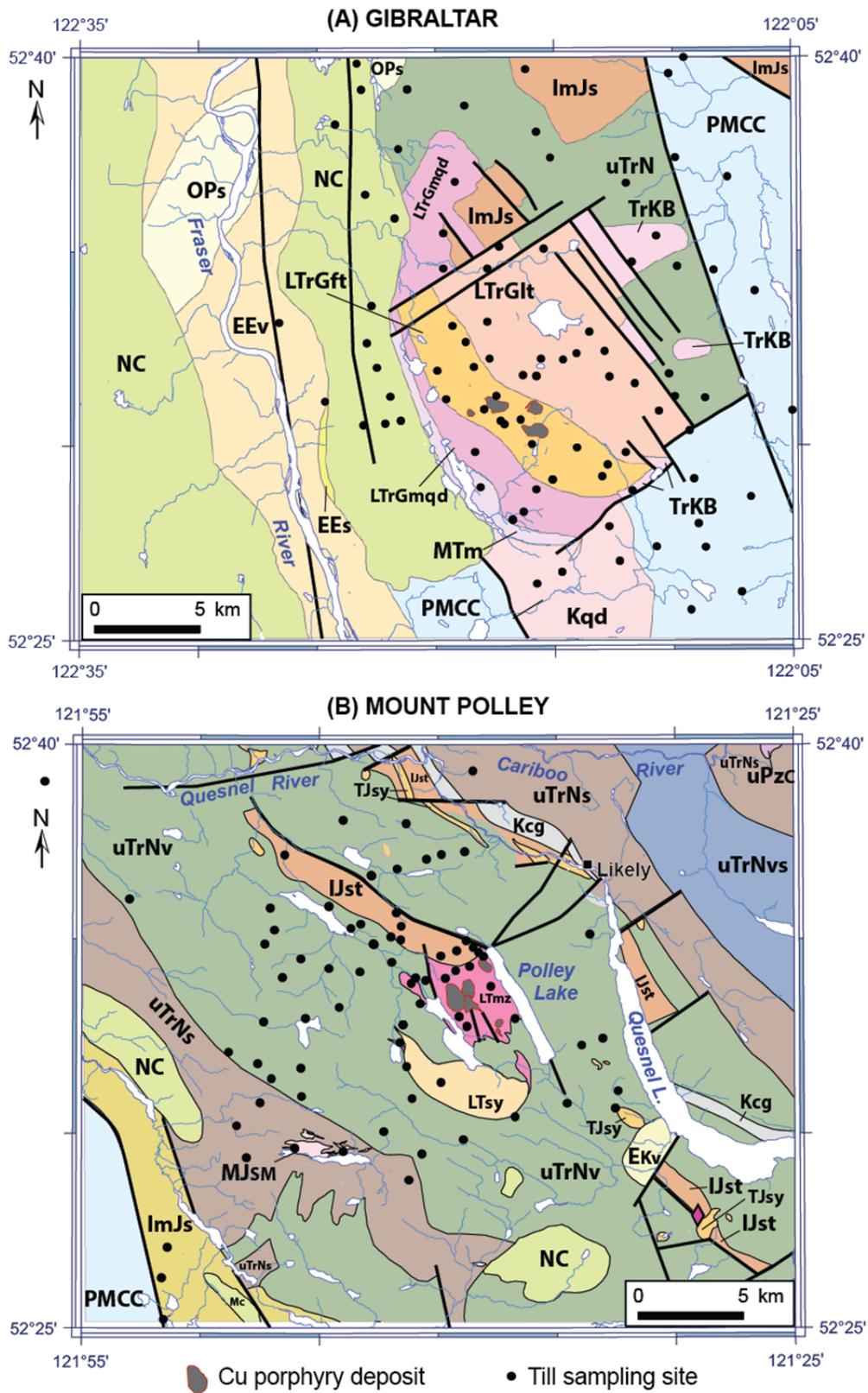


Figure 8. Maps with location of till sampling sites in the region of the (A) Gibraltar deposits and (B) Mount Polley deposits. The bedrock legends are the same as figures 2 and 3.

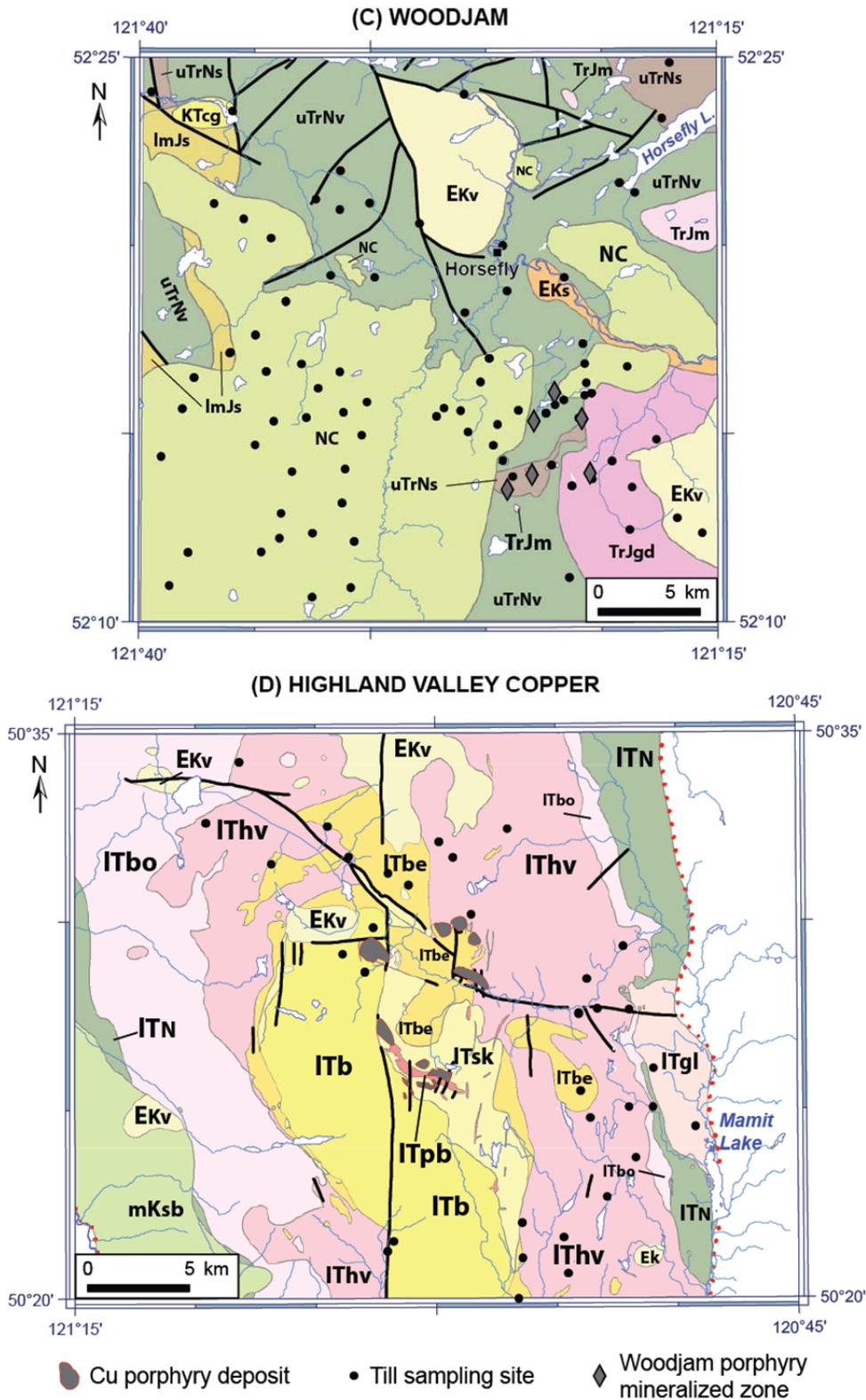


Figure 8. Continued. Maps with location of till sampling sites in the region of the (C) Woodjam prospect and (D) Highland Valley Copper deposits. The bedrock legends are the same as figures 4 and 5.

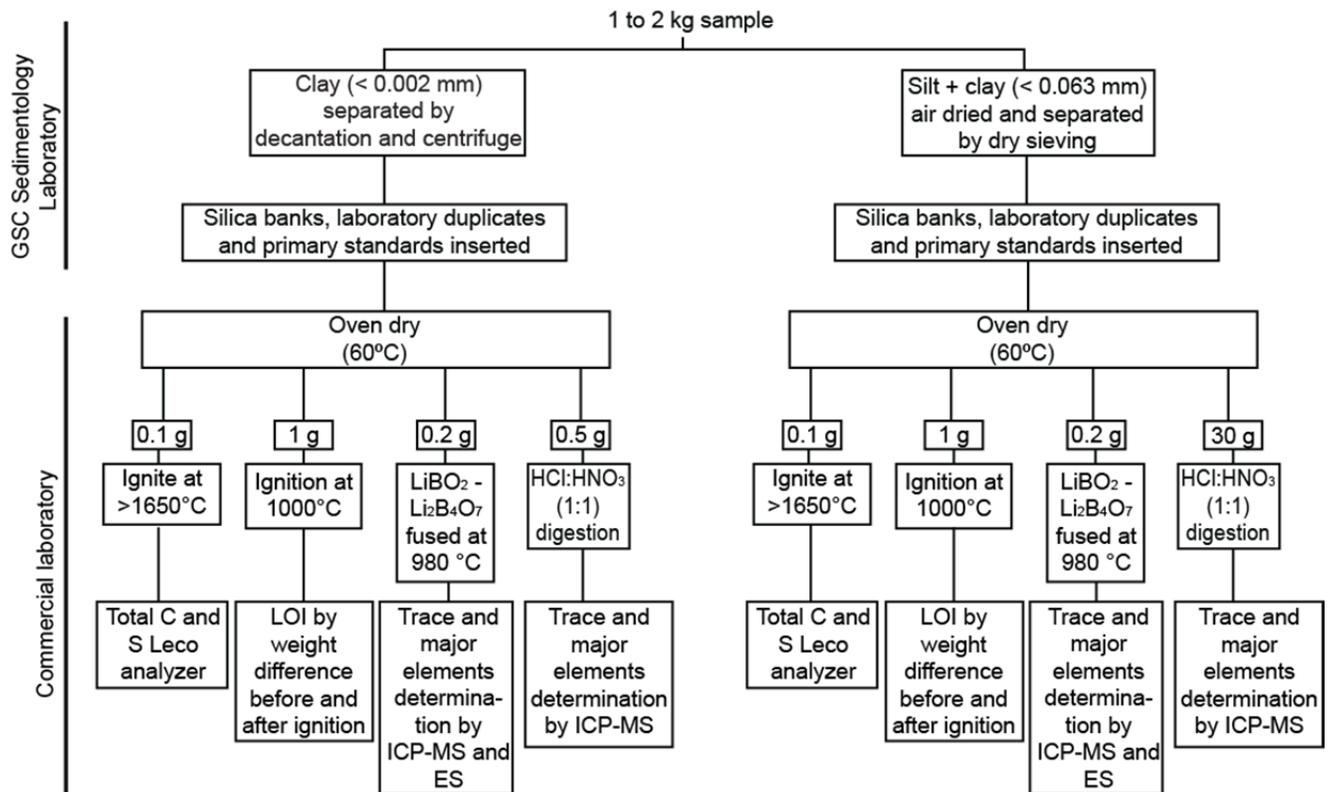


Figure 9. Flow chart for the processing of samples for geochemical analyses (from Plouffe and Ferbey, 2015a).

with SG >3.2 was submitted to paramagnetic separation using a Carpco[®] magnetic separator set at 0.6, 0.8 and 1 amp to facilitate mineral identification based on magnetic properties (McClenaghan, 2011; Plouffe et al., 2013c). The 0.25-0.5 mm, 0.5-1 mm and 1-2 mm fractions in the 2.8-3.2 and > 3.2 SG fractions were examined for minerals potentially indicative of mineralization (Magmatic or metamorphosed massive sulphide indicator minerals – MMSIM[®] and Pophyry Copper Indicator Minerals – PCIM[®] packages at ODM) with the use of a binocular microscope. Minerals were identified based on colour, crystal habit, luster, cleavage and surface textures. For a limited number of grains, optical mineral identification was qualitatively verified with a scanning electron microscope (SEM). The percentage of green epidote was estimated from the 0.25 to 0.5 mm, SG >3.2, and 0.8-1.0 amp fraction. The unmodified laboratory reports produced by ODM are included in Appendix 4A (2011), 4B (2012 part 1), 4C (2012 part 2) and 4D (2013).

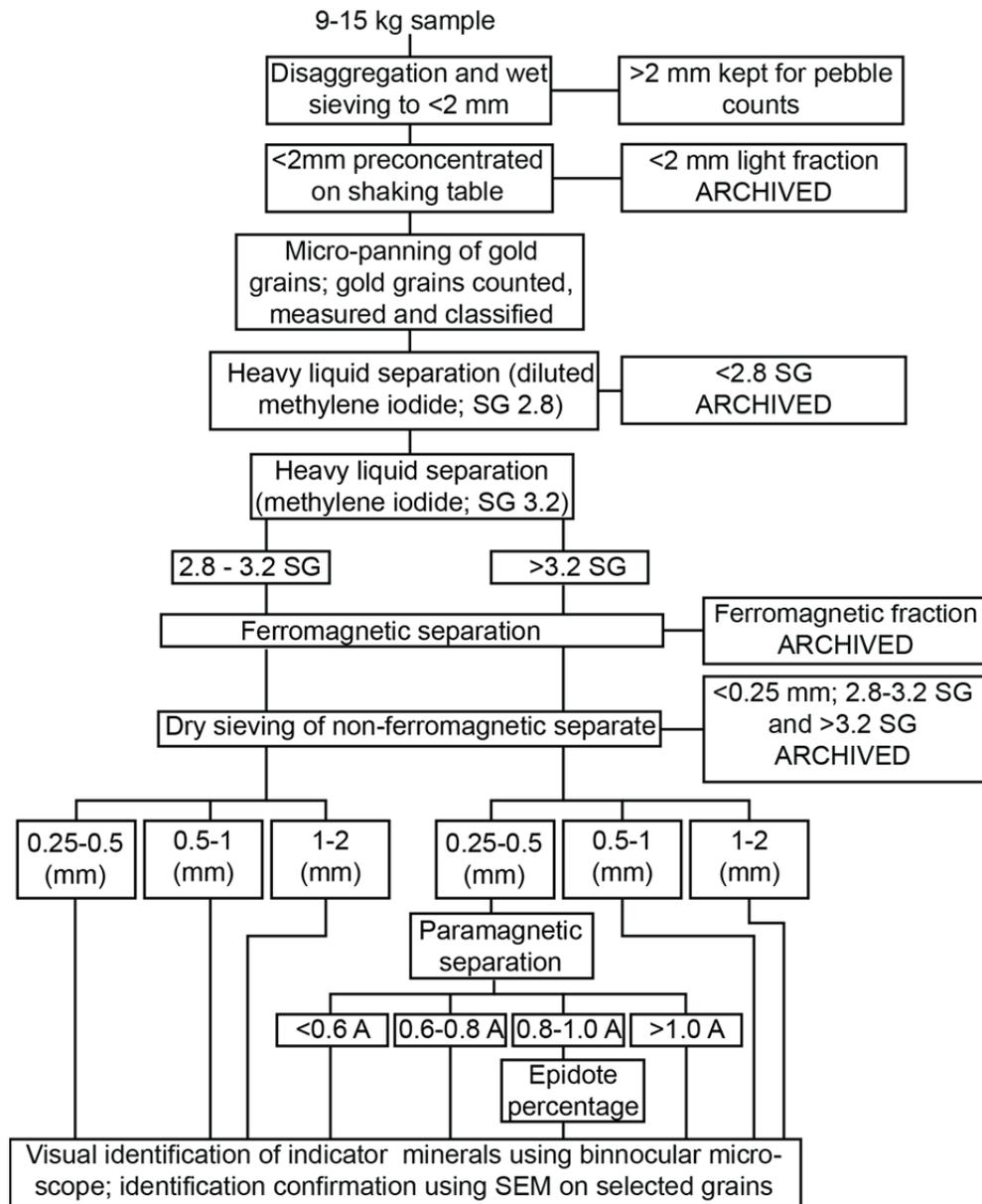


Figure 10. Flow chart for indicator mineral processing and identification (modified from Plouffe and Ferbey, 2015a).

Grain size determinations

Grain-size determinations of the till matrix were completed in the Sedimentology Laboratory of the GSC. Approximately 200-300 g from each 1-2 kg sample was wet sieved to obtain the >0.063 mm fraction of the samples. Size fractions 0.063 to 2 mm were determined by wet sieving followed by digital image processing using a CAMSIZER particle size analysis system. The size classes smaller than 0.063 mm were determined using a Lecotrac LT100 Particle Size Analyser on a separate split. A total of 164 samples were submitted for a complete grain size determination with the objective of

evaluating the variation in till texture throughout the four study sites. Approximately half the samples were processed for grain-size analysis. Grain-size determinations are reported in Appendix 5.

Quality assurance / quality control (QA/QC) measures

Geochemical analyses

Field and laboratory duplicates, standards and silica blanks were inserted in the sample suite sent for geochemical analyses to estimate sediment heterogeneity, to monitor precision and accuracy of geochemical analyses and carry-over contamination in between samples (memory effect). Field duplicates were collected at approximately one site out of 20. At a field duplicate site, the duplicate sample was collected within the same sedimentary unit and the same sample hole as the routine sample to evaluate sediment heterogeneity. Because the duplicate samples were collected from the same hole as the routine sample, this approach measures sediment heterogeneity over a limited spatial extent. Following procedures outlined in Spirito et al. (2011) and McClenaghan et al. (2013), blind duplicates (laboratory duplicates) were prepared by splitting the separated size fraction (clay or silt plus clay) of the field duplicates into two samples. Those two samples, that is the blind and field duplicates are considered homogenized and are used to evaluate analytical precision. The primary standards Till-3 and Till-4 were inserted in the sample suite to evaluate analytical accuracy (Lynch, 1996). Lastly, silica blanks were included to monitor carry over from one sample to the next. Approximately, one standard and one silica sample were inserted for every 20 routine samples.

Several methods exist to evaluate analytical precision (see Abzalov, 2008 for a review). The GSC Laboratory Information Management System defines the analytical precision as the relative standard deviation (%), calculated following the method outlined in Garrett (1969), but without log normally transforming the analytical values.

Precision

Results of the blind duplicates and estimated analytical precisions are provided in Appendices 2D (2011), 2E (2012), and 2F (2013) for the clay-sized fraction and in Appendices 3D (2011), 3E (2012), and 3F (2013) for the silt plus clay-sized fraction. Results of the primary standards and silica blanks submitted with the clay-sized fraction are included in Appendices 2G (2011), 2H (2012), and 2I (2013) and submitted with the silt plus clay-sized fraction in Appendices 3G (2011), 3H (2012), and 3I (2013).

Results of blind duplicates indicate that the analytical precision is in most cases $\leq \pm 15\%$ relative standard deviation (RSD) (Appendices 2D, 2E, 2F, 3D, 3E, 3F). The precision is $> \pm 15\%$ for elements with determinations close to detection limit (e.g. Nb, Se, Te) or for elements known to be heterogeneously distributed as discrete particles in the analytical medium (e.g. Au). In the case of Au, the analytical precision is generally better in the clay-sized compared to the silt plus clay-sized fraction. For example, for the 2012 analyses, the precision of Au determinations is $\pm 19\%$ in the clay and $\pm 48\%$ in the silt plus clay (Appendices 2E and 3E). Likewise, for the 2013 analyses, the precision for Au is $\pm 11\%$ in the clay and $\pm 52\%$ in the silt plus clay (Appendices 2F and 3F). This likely reflects a greater homogeneity of Au in the clay compared to the silt plus clay fraction.

Two pairs of laboratory duplicate samples of clay material submitted in 2012 for ICP-ES+MS (metaborate/tetraborate, fusion) have returned anomalous results: 1) 12TFE101A01 and 12TFE130A02 returned 647 and 131 ppm Ni, and 2) 12PMA583A01 and 12PMA614A02 returned 56 and 15 ppm Pb (Appendix 2E). Similarly, for the same year and following the same analytical method, a pair of laboratory duplicate samples from the silt plus clay fraction (12PMA571A01 and 12PMA530A02) returned inconsistent results of 748 and 67 ppm Ni, respectively (Appendix 3E). Given that these laboratory duplicates were homogenized during their preparation, the variability is unlikely related to sample heterogeneity. To investigate these questionable results, a number of samples analyzed before and after the problematic samples were resubmitted for analyses. Re-analyses reveal that the spurious results are isolated to a single sample (Appendix 2J and 3J). By comparing original laboratory duplicate, and re-analysis results, the following corrections were made: 1) 12TFE101A01 Ni content in clay-size fraction was corrected to 109 ppm (Appendix 2J), 2) 12PMA583A01 Pb content in clay-size fraction was corrected to 18 ppm (Appendix 2J), and 3) 12PMA571A01 Ni content in the silt + clay-size fraction was corrected to 49 ppm (Appendix 3J). These corrections are included in the 2011, 2012 and 2013 compilation for the clay (Appendix 2L) and the silt + clay (Appendix 3L) size fractions.

Accuracy

Analytical results on the two primary standards (Till-3 and Till-4; Lynch, 1996) and the silica blanks used in this study are reported in Appendices 2G, 2H, 2I, 3G, 3H and 3I. Results are presented on separate worksheets and are divided by material (silica blank = qtz-C49643, Till-3 and Till-4) and analytical method. The legend included on each worksheet indicates the certified (underline), provisional (in parentheses) and informational (plain text) concentrations of the primary standards. As

indicated in the legend, the threshold has been placed at two standard deviation of the certified, provisional or informational concentration. Any measured concentration that is outside of the two standard deviation appears in red on the worksheet. Analytical results on the two primary standards are within or very close to two standard deviation of the certified or provisional concentrations. These results indicate that analytical determinations for all methods are accurate for most elements.

Most analyses of silica blanks have returned satisfactory results (i.e. elemental concentrations below or very close to detection limit except for SiO₂, Sr and Zr which are elements expected in the silica samples). Zirconium concentrations are typically three to eight times more elevated following analyses after the metaborate/tetraborate fusion compared to the modified aqua regia leach indicating that zirconium is dominantly present in a silicate phase, likely zircon, which is not dissolved in HCl:HNO₃ (1:1).

Anomalous analytical results were detected for Zn (12 ppm) and Cu (11 and 664 ppm) determinations by ICP-ES+MS after the metaborate/tetraborate fusion on the silicate blanks submitted with the 2013 silt plus clay size fractions (Appendix 3I). To investigate these anomalous results, the silica blanks and eleven silt plus clay samples analyzed before and after the anomalous silica blanks were re-analyzed (Appendix 3K). Reanalysis of the silica samples returned acceptable results for Zn and Cu determinations. However, one sample returned a high V concentration (23 ppm) which is anomalous for a silica blank sample (Appendix 3K). The V concentration in silica blank is typically <8 ppm. Elemental concentrations in other routine samples submitted with the silica blanks have not changed significantly except for the Ni concentrations in two pairs of duplicate samples which show poor reproducibility (61 and 37 ppm in one pair and 64 and 145 ppm in a second pair) (Appendix 3K).

In light of these results, we recommend that the Ni, Pb, Cu, Zn, and V determinations by ICP-ES+MS after the metaborate/tetraborate fusion be used with caution.

Analysis of variance (ANOVA)

As part of the QA/QC measures, an analysis of variance (ANOVA) was completed with the field duplicate samples to compare the variability between sampling sites (between site) and between duplicate samples (within site). For a geochemical data set to be statistically significant and to reflect spatial variability related to a geological factor (e.g. mineralization), variability between sites need to be greater than variability between field duplicate samples. The ANOVA was completed for a selected group of elements that can be significant for geochemical exploration for Cu porphyry deposits. The

ANOVA was completed with geochemical results on the clay- and the silt plus clay-sized fractions using “R” (R Core Team, 2015) and “rgr” (GSC Applied Geochemistry EDA Package) (Garrett, 2013; 2015). Results below detection limit and samples with insufficient material for analysis were ignored from calculations (McCurdy and Garrett, 2016). Results are tabulated in Table 1 for the clay- and Table 2 for the silt plus clay-sized fractions. The tables include the number of sample pairs (one pair equals one routine and one field duplicate sample), the percentage related to the variability between site and within site (i.e. between field duplicate samples), the variance ratio (F) and the confidence level (p-value). The variance ratio (F) gauge whether the variance ‘within’ is significantly smaller than the variation ‘between’ sites.

For all tested elements, the ANOVA indicates that the variability is greater between sites compared to between duplicate samples at a confidence level that exceeds 95% ($p < 0.05$). Furthermore, F values are all higher than 4 which corresponds to the lower acceptable threshold for a geochemical data set to be suitable to reflect spatial variability (McCurdy and Garrett, 2016). The ANOVA suggests that the geochemical results for the tested elements reflect geological variability as oppose to analytical artefacts.

Table 1. ANOVA completed on the analytical results from field duplicate and routine samples of the clay-sized fraction (<0.002 mm).

Element	Method	n-pair	Between site	Within site	F	p-value
Ni	Li*	15	73.7	26.3	6.59	0.0004
Cu	Li*	15	99.2	0.8	246.62	<0.0001
Zn	Li*	15	99.3	0.7	298.61	<0.0001
Mo	Li*	9	90.4	9.6	19.92	0.0001
Pb	Li*	15	97.2	2.8	71.2	<0.0001
V	Li*	15	85.9	14.1	13.19	<0.0001
Mo	Ar**	15	99.8	0.2	1087.23	<0.0001
Cu	Ar**	15	99.1	0.9	216.61	<0.0001
Pb	Ar**	15	97.8	2.2	89.22	<0.0001
Zn	Ar**	15	98.6	1.4	143.6	<0.0001
Ag	Ar**	15	93.4	6.6	29.2	<0.0001
Ni	Ar**	15	99.0	1.0	195.13	<0.0001
Co	Ar**	15	96.8	3.2	62.27	<0.0001
Au	Ar**	15	71.6	28.4	6.05	0.0007

*Li – LiBO₂/Li₂B₄O₇, fusion ICP-ES+MS; **Ar – HCl:HNO₃, ICP-MS

Table 2. ANOVA completed on the analytical results from field duplicate and routine samples of the silt plus clay-sized fraction (<0.063 mm).

Element	Method	n-pair	Between site	Within site	F	p-value
Ni	Li*	14	93.2	6.8	28.39	<0.0001
Cu	Li*	14	96.3	3.7	53.05	<0.0001
Zn	Li*	14	96.2	3.8	52.05	<0.0001
Mo	Li*	7	88.7	11.3	16.71	0.008
Pb	Li*	11	92.0	8.0	24.15	<0.0001
V	Li*	14	90.3	9.7	19.64	<0.0001
Mo	Ar**	15	93.2	6.8	28.57	<0.0001
Cu	Ar**	15	99.7	0.3	621.56	<0.0001
Pb	Ar**	15	96.7	3.3	60.09	<0.0001
Zn	Ar**	15	97.6	2.4	83.78	<0.0001
Ag	Ar**	15	95.3	4.7	41.94	<0.0001
Ni	Ar**	15	99.5	0.5	431.84	<0.0001
Co	Ar**	15	98.0	2.0	97.13	<0.0001
Au	Ar**	15	60.1	39.9	4.02	<0.006

*Li – LiBO₂/Li₂B₄O₇, fusion ICP-ES+MS; **Ar – HCl:HNO₃, ICP-MS

Indicator mineral processing and identification

Four procedures were followed to assess the accuracy and precision of heavy (>3.2 SG) and mid-density (2.8-3.2 SG) mineral separations, and mineral identification, as outlined in Plouffe et al. (2013c). First, field duplicates were collected at one site out of 20 (same sample site as duplicate samples collected for geochemical analyses), in the same sample hole as the routine sample to estimate sediment heterogeneity over a limited spatial extent.

Second, blank samples consisting of material from a weathered granite (grus) from New Brunswick (see Plouffe et al., 2013c) were inserted in the sample suite prior to shipping for processing. A blank sample was included as the first sample to monitor carry over (contamination) from previously analyzed samples in the processing laboratory. Also, a blank sample was inserted approximately every 20th sample to monitor cross-contamination in between samples.

Third, till from Almonte, Ontario, with a known mineral assemblage (see Plouffe et al., 2013c), was spiked with gold and chalcopyrite grains to monitor the accuracy of the heavy mineral separation and identification procedures. A total of three spiked samples were analyzed from 2011 to 2013. In 2011, one sample was spiked with twelve gold grains obtained from sample 08PMA-A102A1 (original results of that sample reported in Plouffe et al., 2009). In 2012, one sample was spiked with nine chalcopyrite grains from samples 08-BAK-S069-L and 08-BAK-K168T (original results of those

samples reported in Kjarsgaard et al., 2013). In 2013, one sample was spiked with 15 chalcopyrite grains from sample 12PMA503A01 (original results reported in here). Spiked grains introduced in the Almonte till were described and photographed to attempt a correlation with the recovered grains from the spiked samples.

Fourth, six heavy mineral concentrates from 2011, and 15 from 2012, were renumbered and resubmitted for indicator mineral identification to monitor precision of the mineralogical identification and numerical counts (percentages and grain counts). Grains picked during the first mineral identification were not returned to the heavy mineral concentrates prior to the second identification (recount). Results of the recounts are presented in unmodified reports produced by ODM in Appendices 4E (2011) and 4F (2012). Results for blank, spiked base material, recounts and field duplicates are tabulated in a number of worksheets in Appendix 4G. Interpretation of the QA/QC results follow.

Blank samples (weathered granite)

The eight blank samples from the weathered granite show no indication of cross-contamination between samples or from previous sample batches. The single modified gold grain recovered from the blank material is not considered anomalous as the weathered granite from New Brunswick is known to contain the occasional gold grain (Plouffe et al., 2013c). The reporting of 80% blond titanite in one blank sample is most likely related to a mineral misidentification. It could represent the heterogeneous distribution of titanite in the granite, but titanite is not known to occur in such large amount in the granite.

Spiked samples

Most of the spiked grains were recovered and correctly identified by the laboratory (ODM). Eleven out of twelve gold grains (50 to 250 microns) were recovered from sample 11PMA023A02 which represents a recovery of 92% (Appendix 4G). Eight out of nine chalcopyrite grains were recovered from sample 12PMA133A01 representing a 89% recovery. In this case, recovered chalcopyrite grains were confirmed by comparing photographs of spiked and recovered grains (Appendix 4H). In a second sample (13TFE001A01), 15 chalcopyrite grains were introduced and 11 were recovered which represents a recovery of 73%. One spiked chalcopyrite grain in the 0.5-1 mm size range, consisting of a small chalcopyrite grain attached to quartz (Appendix 4H), was not recovered. This lithic fragment might have broken down during sample processing therefore liberating the chalcopyrite grain.

Photographs of grains taken prior to spiking were reviewed, with a focus on grain morphology, but this particular grain could not be identified in the recovered concentrate (Appendix 4H). To overcome this problem in future projects, additional photographs could be taken to show grain morphology on different faces or spiking grains could be laser etched.

Recounts

Review of the recount results provided in Appendix 4G show that there is limited variability in original and recount results. Certain differences can be accounted for by the fact that grains picked in the original sample were not re-introduced in the sample submitted for recount; these instances are highlighted in yellow in Appendix 4G. Tourmaline percentages, reported on the porphyry Cu indicator mineral data sheet, in the recount and the original samples are very close to each other for most samples. However, in seven sample pairs, small amounts of tourmaline (<20 grains) were missed in either the recount or original sample. Estimates of green epidote in the original and recount samples are in good agreement except in one case where the first estimate (15%) is significantly different from the second (50%) (sample 11-PMA-051A1 and 11-PMA-105A-1).

Field duplicates

In general, results of field duplicate samples (Appendix 4G) indicate that within a limited spatial extent, till mineralogy is relatively consistent. However, there are a couple of exceptions. For example, the duplicate pair 11PMA009A1 and A2 contains 5 and 1 gold grains and a second pair 13PMA005A1 and A2 contains 0 and 5 gold grains. The duplicate pair 12TFE114A01 and A02 contains 50 and 0 andradite grains, and a second pair 11PMA013A1 and A2 contains trace amount and 9% of tourmaline.

QA/QC summary

In summary, QA/QC results indicate that geochemical and mineralogical results obtained as part of this project are fit to represent the spatial variability in till in the region of the four study sites. In other words, variability in the composition of till is in large part controlled by geology and sample site variability and not by analytical artefacts. Potentially spurious results were obtained as part of the geochemical analyses but re-analyses of a number of samples reveal that the analytical problems were isolated to single analysis. Nickel, Pb, Cu, Zn, and V determinations by ICP-ES+MS after the

metaborate/tetraborate fusion should be used with caution given the number of detected and corrected analytical anomalies.

Grain size analysis of the till matrix

Grain size results tabulated in Appendix 5 are graphically presented in ternary plots in Figure 11 based on Folk's (1954) classification system. The plots were created with Gradistat (v. 8). These results show that the majority of till samples collected as part of this study have a sandy silt matrix. Samples from Gibraltar, Mount Polley and Woodjam have a relatively similar grain-size composition, most likely related to the similar bedrock lithologies at these three sites that is a mixed source of intrusive and volcanic rocks. On the other hand, till in the Highland Valley region generally contains more sand than the other three study sites. This is most likely related to the predominant source material for the till being the Guichon Creek batholith (dominantly medium grained and granodioritic in composition) which underlies most of the study area. The predominance of granitic clasts in till in the region of the Highland Valley region also points to the large granitic bedrock source of the region, the Guichon Creek batholith (Appendix 4I).

Geochemical and mineralogical data in a Geographic Information System (GIS)

Geochemical analytical results for the 2011, 2012 and 2013 samples are combined into two files with location information (easting, northing and, latitude, longitude) for the clay-sized fraction (Appendix 2L) and the silt plus clay-sized fraction (Appendix 3L), in a Microsoft Excel 2011 format (.xlsx).

Presentation of the geochemical data sets in this format facilitates their use in geographic information systems (GIS) software. In addition, both files are provided as shapefiles (Appendices 2M and 3M).

Similarly, mineralogical results for 2011, 2012 and 2013 were extracted from the original laboratory reports and tabulated (with sample location information) in a Microsoft Excel 2011 format (.xlsx) (Appendix 4I). Table 3 defines column headings used in this appendix. To allow the use of all mineralogical and lithological data in a GIS, mineral and clast lithology abundances reported by ODM as trace amounts (Tr.) were converted to a numerical value of 0.1. This is the case for olivine, apatite, goethite, tourmaline, granitic clasts (GR) and volcanic/sedimentary clasts (V/S). Given that the presence or absence of specific minerals have implications for mineral exploration purposes, and that

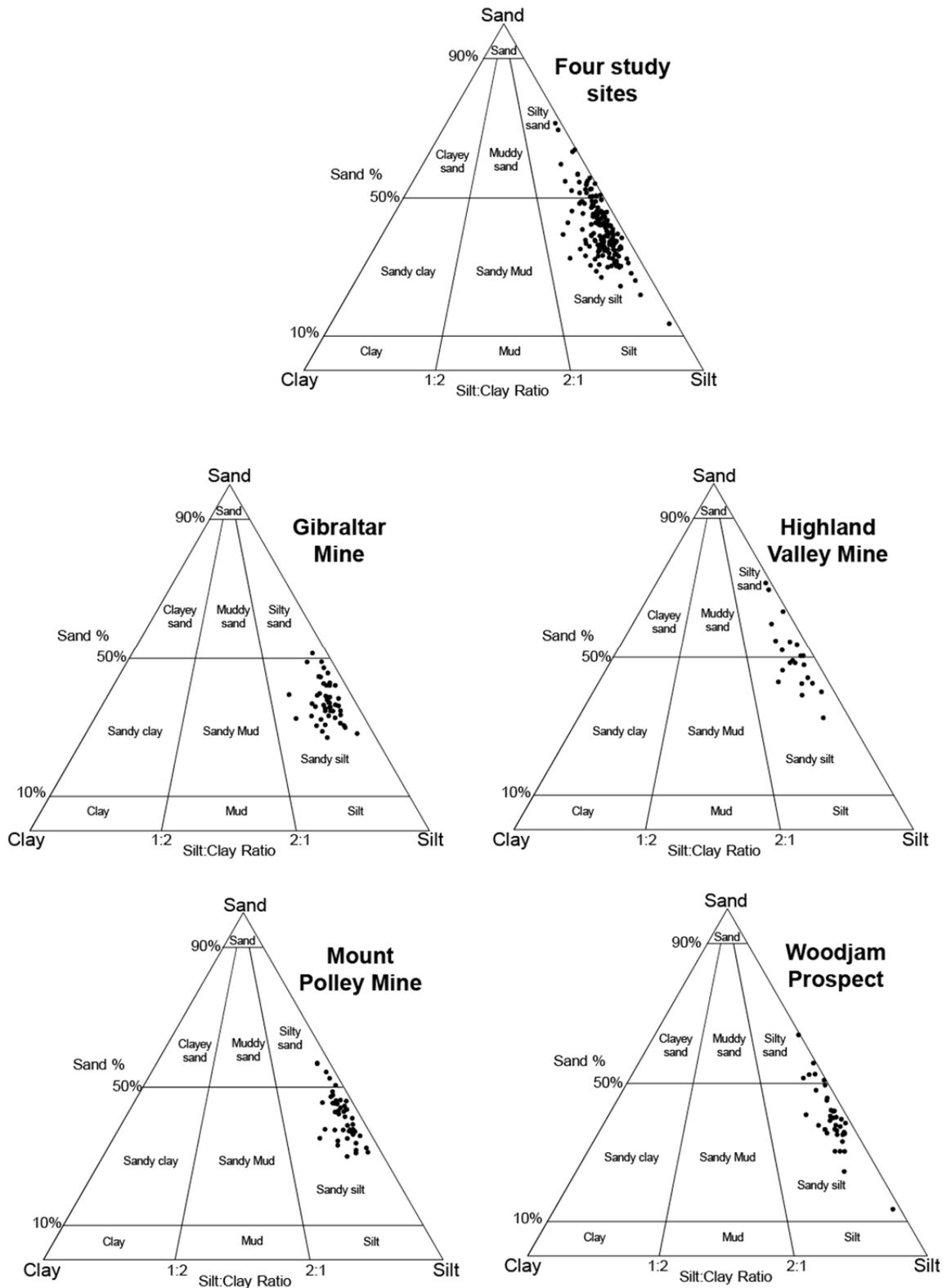


Figure 11. Ternary diagrams showing the percentage of sand ($2 - >0.063$ mm), silt ($0.063 - >0.002$ mm) and clay (<0.002 mm) in the till matrix at the four study sites separately and grouped. Following Folk's (1954) classification.

some of those minerals are heterogeneously distributed in till (e.g. gold grains, andradite, tourmaline), results from both the routine and the duplicate samples were preserved in Appendix 4I. The same file is provided as a shapefile (Appendix 4J).

Table 3. Appendix 4I column headings and their definition.

Heading	Definition	Heading	Definition
Table_Feed	Table feed (kg)	gr_Mn_oxide	Number of grains of manganese oxide
Table_Feed_N	Table feed divided by 10 kg; value used to normalized indicator mineral counts to 10	gr_Rd_Rtite	Number of grains of red rutile
GG_Tot	Total number of gold grains	%_Bld_Ttn	Percentage of blond titanite
ReGG	Number of reshaped gold grains	gr_Ase	Number of grains of arsenopyrite
MoGG	Number of modified gold grains	%_Ky_Sil	Percentage of kyanite and sillimanite
PrGG	Number of pristine gold grains	%_Tm	Percentage of tourmaline (>3.2 S.G.)
Ca_GG_Tot	Calculated gold concentrations (ppb) based on total number and size of gold grains	%_St	Percentage of staurolite
Ca_ReGG	Calculated gold concentrations (ppb) based on the number and size of reshaped gold grains	%_Ol	Percentage of olivine
Ca_PrGG	Calculated gold concentrations (ppb) based on the number and size of pristine gold grains	%_Opx	Percentage of ortho-pyroxene
V/S	Estimated percentage of volcanic and sedimentary clasts in the >2 mm size fraction	gr_Cr	Number of grains of chromite
GR	Estimated percentage of granitic clasts in the >2 mm size fraction	%_Ap	Percentage of apatite
LS	Estimated percentage of limestone or carbonate clasts in the >2 mm size fraction	%_Mz	Percentage of monazite
OT	Estimated percentage of other lithologies in the >2 mm size fraction	gr_Rse_Zrc	Number of grains of rose zircon
gr_Cpy	Number of chalcopyrite grains	gr_Cu_cpy	Number of chalcopyrite grains reported with copper porphyry indicator minerals (2.8-3.2 SG)
gr_arsenopy	Number of arsenopyrite grains	Cu_ind_gr	Number of prime Cu porphyry minerals
gr_gahnite	Number of gahnite grains	gr_Jarsite	Number of jarosite grains
gr_mlchite	Number of malachite grains	%_alunite	Percentage of alunite
barite	Number of barite grains	gr_Trmline	Number of tourmaline (2.8 – 3.2 S.G.)
chalcocite	Number of chalcocite grains	%_Epdte	Percentage of green epidote (>3.2 S.G., 0.25-0.5 mm, 0.8-1 Amp)

Heading	Definition	Heading	Definition
gr_Py	Number of pyrite grains	Cpy_05_1	Number of chalcopyrite grains in the 0.5-1 mm fraction
%_Gth	Percentage of goethite	Cpy_1_2	Number of chalcopyrite grains in the 1-2 mm fraction
gr_And	Number of andradite grains	Jar_05_1	Number of jarosite grains in the 0.5-1 mm fraction
Mn_epdte	Number of Mn epidote	Jar_1_2	Number of jarosite grains in the -2 mm fraction
Low_Cr_dps	Number of low-Cr diopside	Mn_epd_05_1	Number of manganese epidote in the 0.5-1 mm fraction
sphre_crdm	Number of sapphire corundum grains	Mn_epd_1_2	Number of manganese epidote in the 1-2 mm fraction
topaz	Number of topaz grains	Red_ru_05_1	Number of red rutile grains in the 0.5-1 mm fraction
rby_crdm	Number of ruby corundum	Malach_1_2	Number of malachite grains in the 1-2 mm fraction
spinel	Number of spinel grains	Magnetic	Weight of magnetic fraction in the 0.25-2 mm size fraction
chondrodi	Number of chondrodite grains		

Interpretation of geochemical and mineralogical results

Till geochemical and mineralogical maps along with preliminary interpretation of results have been provided in the following publications: Hashmi et al. (2013, 2014, 2015b, c), Plouffe et al. (2013a, b, 2014, 2015), Hashmi (2015), and Plouffe and Ferbey (2015a, d). Furthermore, as part of this project, research on indicator mineral composition was completed for magnetite (Grondahl, 2014; Piziak et al. 2015; Canil et al. 2016), tourmaline (Chapman et al. 2015a, b), and apatite (Rukhlov et al. 2016). Similar detailed study on epidote group minerals, titanite and rutile is currently on-going by C. Kobylinski at the University of Ottawa under the supervision of K. Hattori (Kobylinski et al., 2016).

Papers to be published in scientific journals with a detailed interpretation of till geochemical and mineralogical results specific to the Gibraltar, Highland Valley Copper and Woodjam deposits are in progress.

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