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Critical review

B. McClenaghan

Authors

T. Ferbey (Travis.Ferbey@gov.bc.ca)
British Columbia Geological Survey
5th Floor, 1810 Blanshard Street
Victoria, British Columbia
V8W 9N3

A. Plouffe (Alain.Plouffe@NRCan-RNCan.gc.ca)
Geological Survey of Canada
601 Booth Street
Ottawa, Ontario
K1A 0E8

R.G. Anderson (Bob.Anderson@NRCan-RNCan.gc.ca)
Geological Survey of Canada
625 Robson Street
Vancouver, British Columbia
V6B 5J3

Correction date:

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Abstract: The Geological Survey of Canada (GSC) and the British Columbia Geological Survey (BCGS) are developing surficial geochemical and mineralogical methods for the detection of buried porphyry-style mineral deposits in drift-covered areas under the federally-funded Targeted Geoscience Initiative 4 Program. One objective is to help define the key components of till that are enriched near such deposits including: 1) porphyry indicator minerals that have survived erosion and transport in the subglacial environment and weathering in an oxidizing surficial environment and 2) trace-element content of the till matrix. Glacial dispersal of both components (heavy minerals and till matrix) is being studied at the Highland Valley, Gibraltar, and Mount Polley mines, and the Woodjam developed prospect which include calc-alkaline Cu-Mo, alkaline Cu-Au, and mixed calc-alkaline and alkaline Cu-Mo-Au porphyry deposits. A second objective is to test biogeochemical methods using spruce and pine tree bark as an exploration tool for buried porphyry-style mineralization.

One key contribution of this project will be the reconstruction of the glacial and ice-flow histories at each of the study sites, based on surficial geological mapping and observations of ice-flow indicators on bedrock outcrop. These ice-flow histories will be applied to the interpretation of geochemical and mineralogical dispersal patterns in till and the spatial distribution of commodity and pathfinder elements in plant tissue.

Between 2011 and 2013, 309 basal till samples were collected for till-matrix geochemical analyses and 302 basal till samples were collected for examination of heavy and mid-density mineral fractions. In total, 487 biogeochemical samples consisting of the outer bark of lodgepole pine (*Pinus contorta*) and Engelmann spruce (*Picea engelmannii*) were collected for geochemical analyses.

Résumé : Dans le cadre du programme de l'Initiative géoscientifique ciblée 4 financé par le gouvernement fédéral, la Commission géologique du Canada et la British Columbia Geological Survey élaborent des méthodes géochimiques et minéralogiques appliquées aux matériaux superficiels pour la détection de minéralisations de type porphyrique enfouies sous des matériaux glaciaires. Un des objectifs est de définir les composantes du till qui sont enrichies près d'un tel type de minéralisation dont les suivantes : 1) les minéraux indicateurs de gîtes porphyriques qui ont survécu à l'érosion et au transport dans l'environnement sous-glaciaire et à la météorisation dans un milieu oxydant de surface et 2) le contenu en éléments traces de la matrice du till. La dispersion glaciaire de ces deux composantes (les minéraux lourds et la matrice du till) est étudiée aux mines Highland Valley, Gibraltar et Mount Polley en plus du prospect mis en valeur de Woodjam qui englobent des gîtes porphyriques de Cu-Mo calco-alcalins, de Cu-Au alcalins et de Cu-Mo-Au mixtes, calco-alcalins et alcalins. Un second objectif est de mettre à l'essai des méthodes biogéochimiques en échantillonnant l'écorce de pin et d'épinette comme outil d'exploration de minéralisations enfouies de style porphyrique.

L'une des contributions importantes de ce projet est la reconstitution de l'histoire glaciaire et des écoulements glaciaires à chacun des sites étudiés, en se fondant sur la cartographie géologique des matériaux superficiels et l'observation des indicateurs des écoulements glaciaires sur les affleurements du socle rocheux. La reconstitution des écoulements glaciaires sera utilisée pour l'interprétation de la dispersion géochimique et minéralogique dans le till et la distribution spatiale des substances utiles et des éléments indicateurs dans le tissu des plantes.

Entre 2011 et 2013, 309 échantillons de till de fond ont été recueillis pour des analyses géochimiques de la matrice du till et 302 échantillons du même type de sédiment l'ont été pour l'examen des minéraux lourds et mi-lourds. Au total, 487 échantillons biogéochimiques d'écorce externe de pin tordu latifolié (*Pinus contorta*) et d'épinette d'Engelmann (*Picea engelmannii*) ont été recueillis pour des analyses géochimiques.

INTRODUCTION

A significant portion of mineral exploration expenditures in British Columbia is used to search for porphyry Cu±Au±Mo mineralization (Britton et al., 2012). Much of this exploration activity occurs within British Columbia's Interior Plateau which is underlain by the Stikinia and Quesnellia terranes, and in turn by volcanic-arc assemblages which host producing and past-producing Cu±Au±Mo porphyry and polymetallic vein mines. Although the Interior Plateau has high potential for discovery of additional porphyry-style mineralization (Nelson and Colpron, 2007), it is characterized by limited and isolated bedrock outcrops and thick glacial sediment cover which hinder effective mineral exploration. Exploration programs have therefore come to rely upon geochemical and geophysical methods to assess mineral potential in the region.

Programs undertaken by the Geological Survey of Canada (GSC), the British Columbia Geological Survey (BCGS) and Geoscience BC have helped decrease exploration risk by addressing knowledge gaps about the geological, geochemical, and geophysical character of the Interior Plateau. The acquisition and release of regional till geochemical data and reconstruction of ice-flow histories (Plouffe and Ballantyne 1994; Plouffe et al., 2001, 2009, 2010; Levson, 2002; Ferbey, 2010, 2011), lake and stream sediment geochemical data (Jackaman, 2006, 2007, 2009), airborne electromagnetic, magnetic, and gravity geophysical data (Fiset, 2007; Meyer and Bates, 2008; Farr et al., 2008; Walker and Garrie, 2009), and bedrock geology mapping (Diakow et al., 1997; MacIntyre, 2001; Mihalynuk et al., 2008, 2009) have all contributed to this increased understanding.

The five year (2010–2015) Geological Survey of Canada (GSC) Targeted Geoscience Initiative 4 (TGI-4) Intrusion-related Ore Systems project being delivered in the Cordillera builds on the earlier work of the agencies listed above. Targeted Geoscience Initiative 4 research is focused on developing surficial sediment geochemical and mineralogical methods and developing and testing biogeochemical protocols for the detection of, and vectoring toward, buried Cu±Au±Mo mineralization (Anderson et al., 2012a, b, c).

The TGI-4 mandate is to provide public geoscience knowledge to improve deep mineral exploration effectiveness. It seeks to test a hypothesis that there are distinctive geological, mineralogical, and geochemical footprints that can differentiate not only deposit subtypes but also the degree of fertility of covered (by glacial sediments) or deep mineralization. Specifically, the activities seek to evaluate whether the characteristic alteration zonation of porphyry systems can be identified in overlying till and forest cover and if these characteristic signatures can be used as effective exploration vectors.

STUDY AREA SELECTION

British Columbia's Interior Plateau physiographic region is an ideal area to develop mineral-exploration techniques that aid in identifying concealed porphyry mineralization (Anderson et al., 2012a) because it hosts producing (e.g. Mount Polley, Gibraltar, Endako, Highland Valley, New Afton, and Copper Mountain) and past producing (e.g. Bell, Brenda, Boss Mountain) porphyry Cu±Au±Mo deposits. Its high potential to host additional undiscovered mineralization is unproven due to the dominant glacial sediment cover (including subglacial till) and sparse bedrock outcrop.

Study sites were selected there, in the vicinity of known mineralized zones, to enable development and testing of till and biogeochemical exploration methods to vector toward concealed porphyry mineralization. The areas surrounding the three producing porphyry open-pit mines, Highland Valley (Cu-Mo; Teck Resources), Gibraltar (Cu-Mo; Taseko Mines Limited), and Mount Polley (Cu-Au; Imperial Metals Corporation), and that around Woodjam developed prospect (Cu-Mo-Au; Goldfields and Consolidated Woodjam Copper Corp.), were selected for this study (Fig. 1). The Woodjam study area is unique amongst these four as mine development has not taken place and only natural bedrock exposures occur here. Study area extents are centred on each deposit and defined based on known regional ice-flow patterns. Sampling of subglacial till can therefore take place up- and down-ice of porphyry mineralization, enabling background and elevated geochemical and mineralogical values to be characterized.

Bedrock Geology

Mineralization at each of the four study deposits is associated with Triassic to Jurassic intrusive suites mainly composed of monzonite, granodiorite, and diorite (summarized in Bouzzari et al., 2011 and Anderson et al., 2012a; Fig. 1). At Mount Polley, Woodjam and Highland Valley mines, the intrusions occur within Upper Triassic to Lower Jurassic Nicola Group volcanic-arc rocks. The setting for the Gibraltar deposits differs because the Triassic Granite Mountain Batholith occurs within Permian or older Cache Creek Group sedimentary rocks which define a forearc accretionary assemblage. Unmineralized Neogene Chilcotin Group basalt flows are locally areally extensive in the Interior Plateau and also present a challenge to mineral exploration as they cover older prospective rocks. Mineralized rocks subcrop at each study deposit and were exposed to glacial erosion during the Late Wisconsinan glaciation.

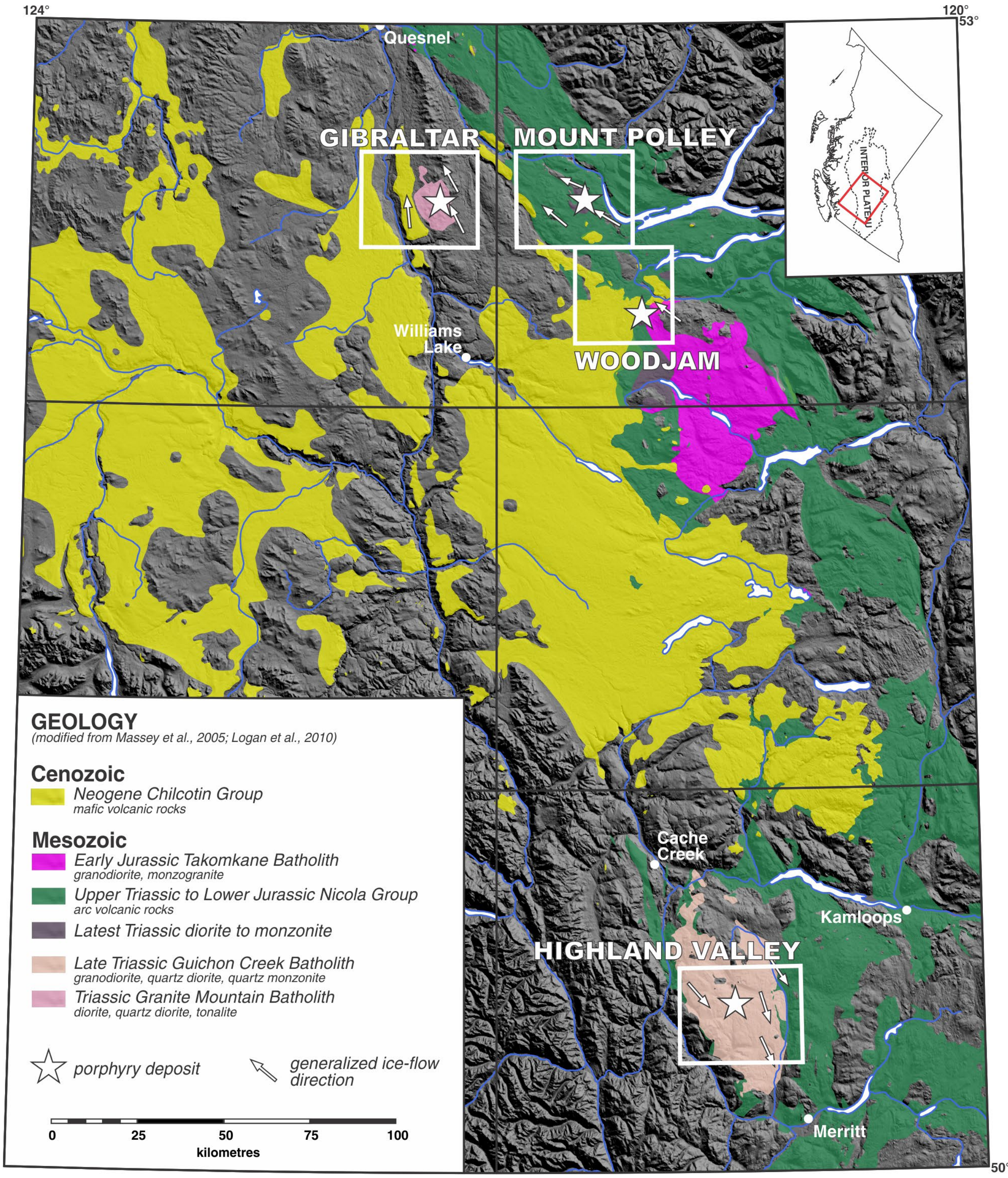

Figure 1. Location of Gibraltar, Mount Polley, Woodjam, and Highland Valley study areas in British Columbia, generalized bedrock geology, and generalized ice-flow directions at glacial maximum. Bedrock geology *modified from* Massey et al. (2005) and Logan et al. (2010).

INDICATOR MINERALS IN MINERAL EXPLORATION

An indicator mineral is a 'mineral whose grains are of practical use for detecting, from afar, a specific type of rock or a specific type of alteration zone or mineralized zone' (Averill, pers. comm, 2012). Additionally, an indicator mineral can suggest the presence of a particular rock type (e.g. kimberlite; McClenaghan, 2005). The minerals are associated with specific geological events (e.g. introduction of metal-rich hydrothermal fluids) and are visually, optically, physically, and/or chemically distinct. If the mineral is to be recovered from surficial sediments such as subglacial till (as when employing drift prospecting methods) then the mineral must have survived glacial erosion, transport, and deposition in the subglacial environment; weathering in an oxidizing surficial environment; and, be easily separated from other minerals that are not of interest (Averill, 2001). Indicator minerals recovered from surficial sediments can be a significant benefit to an exploration program as their presence and composition help refine the bedrock provenance (i.e. style of mineralization and fertility). Compared with interpretation of multisource, multistage enrichments of commodity and pathfinder element values in till or stream sediment samples; an indicator mineral assemblage is interpreted and ideally linked to a specific mineral deposit type or associated alteration zone.

In Canada, most case studies evaluating the utility of indicator minerals have been completed in northern Ontario, Northwest Territories, and Nunavut. For example, indicator minerals recovered from surficial sediments have been used extensively and successfully in Arctic exploration programs for diamond-bearing kimberlite. As a result, compositional and vectoring protocols for kimberlite indicator minerals are relatively well known (Fipke et al., 1995; McClenaghan et al. 2002; McClenaghan and Kjarsgaard, 2007; Stea et al., 2009). The application of indicator minerals has also been developed in mineral exploration for other deposit types such as Ni-Cu-PGE (Averill, 2011; McClenaghan et al. 2013), VMS (McClenaghan et al. 2012a,b), and Au (Averill, 2001, 2009; McClenaghan et al., 2008; McClenaghan and Cabri, 2011).

Scott (2005) and Averill (2011) discuss the use of porphyry indicator minerals (PIMs) recovered from sediments, but these case studies are from unglaciated and arid regions in Australia and Chile. In British Columbia, Plouffe et al. (2011) presented evidence of palimpsest glacial dispersal based on the regional distribution of thorianite grains in till from the Bonaparte Lake region. Gold-grain counts have also been published for regional-scale till surveys conducted in British Columbia (Plouffe, 1995; Plouffe et al., 2009; Ferbey, 2009), but a systematic study on indicator minerals recovered from till samples near Cordilleran porphyry mineralization has not been undertaken until this project.

Bouzzari et al. (2011) have made a significant contribution to the use of PIMs in British Columbia by successfully using apatite luminescence and magnetite replacement textures to differentiate between magmatic and hydrothermal sources for these two minerals. This work was completed on mineral grains recovered from bedrock samples from the Highland Valley and Huckleberry calc-alkaline Cu-Mo porphyry deposits, Mount Polley, Mount Milligan, and Lorraine alkaline Cu-Au porphyry deposits, and Endako calc-alkaline Mo porphyry deposit. Included in their report is a table of resistate minerals that can be associated with porphyry mineralization. The minerals rutile, apatite, garnet, zircon, monazite, titanite, tourmaline, jarosite, and magnetite are listed along with characteristic features, where they can be expected to occur within a mineralized porphyry system, and examples of British Columbia porphyry deposits they occur in. This table, and common heavy minerals discussed by Peuraniemi (1990), are the basis for future PIMs research in British Columbia.

Although there are no published British Columbia studies on the use of PIMs recovered from surficial sediments, Anderson et al. (2011) and Kelley et al. (2011) present a case study on the use of PIMs in glaciated terrain at the Pebble calc-alkaline porphyry Cu-Au-Mo deposit in southwestern Alaska, USA. As part of their study, 70 till samples were processed for indicator minerals with specific gravity >2.8 in the 0.25 to 0.50 mm size fraction. Those mineral concentrates were compared to similar concentrates recovered from 17 bedrock samples collected from mineralized zones. Of the 11 indicator minerals identified in the bedrock and till samples, only gold, pyrite, and apatite occurred in both. The presence of indicator minerals chalcopyrite, chalcocite, and molybdenite in mineralized bedrock, but not in till down-ice from mineralization, is most likely due to glacial comminution and postdepositional weathering in the surficial environment. The presence of andradite garnet, cinnabar, and Mn-rich epidote in till but not in bedrock suggests those minerals could represent the vestiges of glacially eroded bedrock representative of a higher level of the porphyry system than currently in outcrop; this has not yet been proven. Of particular interest is the occurrence of jarosite (hydrous potassium and iron sulphate) in 28 of the 70 till samples down ice. It was not recovered from bedrock samples in their study. Its presence in till suggests that a preglacial supergene cap existed over the Pebble West zone.

TILL SAMPLE MEDIA, ANALYSES, AND SEPARATIONS

Till geochemical surveys are well suited to assessing the mineral potential of ground covered by glacial drift (e.g. Levson et al., 1994; Cook et al., 1995; Levson, 2002; Lett et al., 2006; Plouffe et al., 2010). Subglacial till is ideal for these assessments as it can be considered a first derivative of bedrock (Shilts, 1993), has a predictable transport history related to ice-flow direction, and its dispersal produces a geochemical or mineralogical signal that is areally more extensive than its bedrock source (Levson, 2001; McClenaghan, 2005). This signal, or dispersal train, can be identified in till exposed at surface based on a combination of 1) elemental concentrations in specific size fractions (e.g. silt and clay, <0.063 mm, -230 mesh); 2) mineral assemblages in a specific grain-size and density fraction; and 3) specific rock types identified in the gravel-sized fraction (>4 mm). Dispersal trains can be traced back to a bedrock source, potentially completely concealed, if the area's ice-flow history is sufficiently well known.

In this project, 2 kg subglacial till samples were collected at 309 sample sites for major-, minor-, and trace-element geochemical analyses following protocols outlined by Spirito et al. (2011; Fig. 2, 3). An additional 302 subglacial till samples, each weighing approximately 10 kg, were collected at the same sites for recovery of heavy and mid-density minerals (Fig. 2, 3). Samples were collected at a depth of about 1 m from roadcuts (Fig. 4). Dense road networks provided access to sites both up- and down-ice of porphyry mineralization, based on known and new ice-flow movement direction measurements. An exception was at Highland Valley, where persistent and deep snow on high ground south and southwest of Lornex and Highmont pits during the May 2012 field season prevented access and sample collection.

Till samples collected for major-, minor-, and trace-element analyses were sieved to produce a silt- plus clay-sized fraction (<0.063 mm) and, decanted and centrifuged to produce a clay-sized fraction (<0.002 mm) at the Sedimentology Laboratory, GSC Ottawa, following procedures outlined by Girard et al. (2004). Minor- and trace-element analyses (37 elements) were conducted on splits of the silt- plus clay-sized and clay-sized fractions by inductively coupled plasma mass spectrometry (ICP-MS), following aqua regia digestion. Major- and minor-element analyses were also conducted on a split of the silt- plus clay-sized and clay-sized fractions using inductively coupled plasma emission spectrometry (ICP-ES), following a lithium metaborate/tetraborate

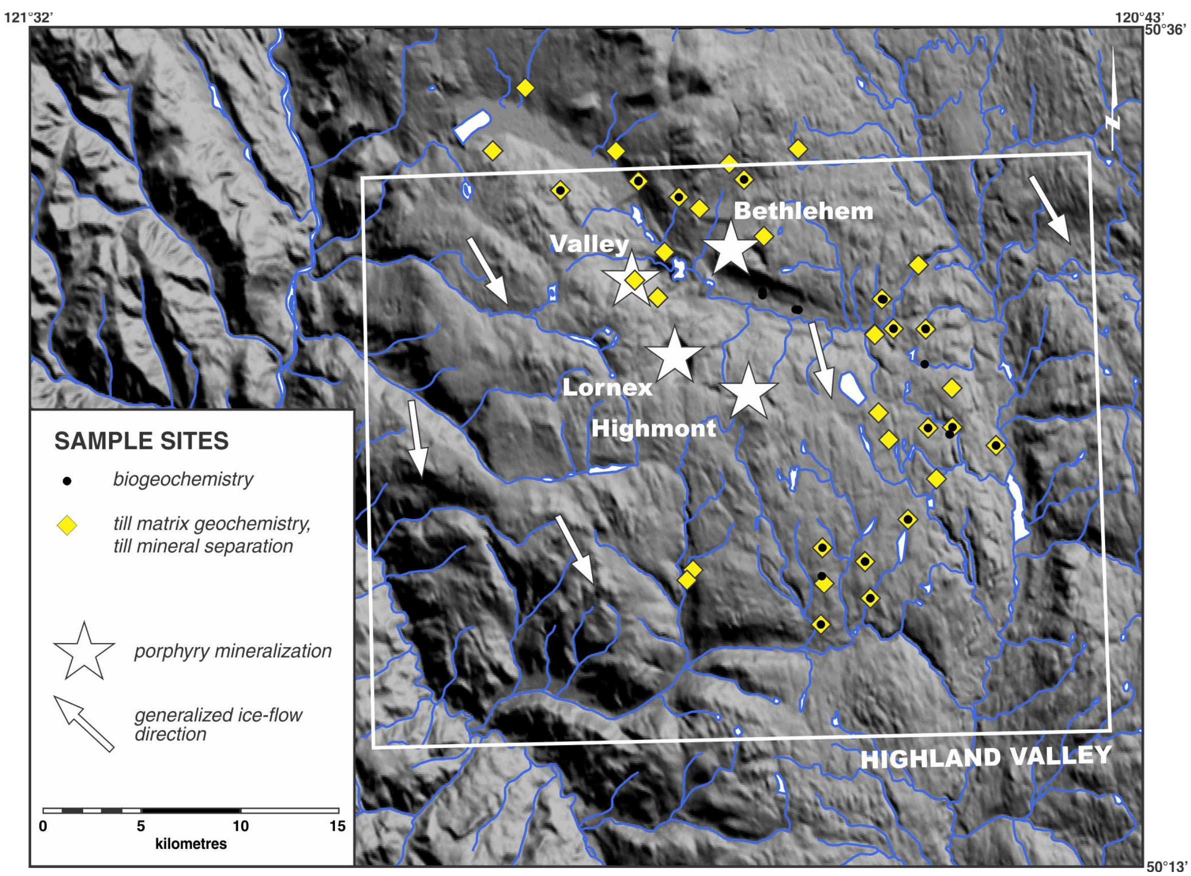

Figure 2. Location of samples for till matrix geochemistry, till heavy mineral separation, and biogeochemistry within the Highland Valley study area. Bethlehem, Highmont, Lornex, and Valley are individual calc-alkaline Cu-Mo porphyry deposits (producing and past producing) located within the Highland Valley mine area. Persistent and deep snow on high ground south and southwest of Lornex and Highmont during the May 2012 field season prevented access and sample collection here. Arrows represent generalized ice-flow direction at glacial maximum.

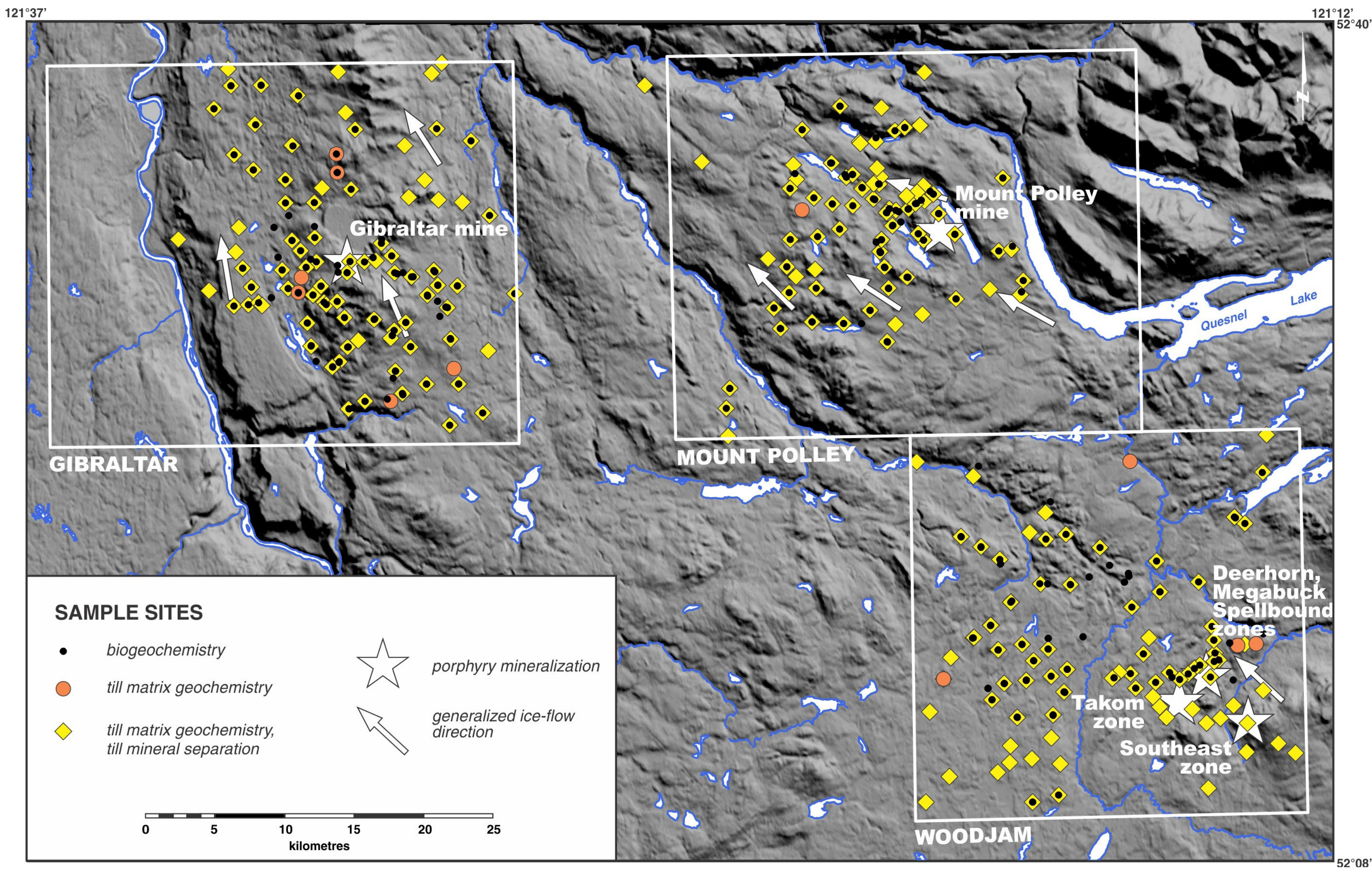

Figure 3. Location of samples for till matrix geochemistry, till heavy mineral separation, and biogeochemistry within the Gibraltar, Mount Polley, and Woodjam study areas. Locations of Gibraltar and Mount Polley mines are shown, as are mineralized zones at the Woodjam developed prospect. Arrows represent generalized ice-flow direction at glacial maximum.

Figure 4. Subglacial till sample site (2 kg and 10 kg samples) in the Gibraltar study area. Pick for scale (110 cm). 2013-264

fusion and dilute nitric acid digestion. This analytical work was conducted by Acme Analytical Laboratories Limited, Vancouver, British Columbia.

Samples collected for recovery of indicator minerals were shipped to Overburden Drilling Management (ODM), Ottawa, Ontario, where heavy (specific gravity >3.2) and mid-density (specific gravity >2.8 to 3.2) concentrates were produced for the 0.25 to 2 mm size fraction. Table concentrates were examined using micro-panning to recover and identify gold and sulphide grains. Although the heavy mineral separation (specific gravity >3.2) is more typically used in indicator-mineral studies, it was important to also produce a mid-density fraction (specific gravity >2.8 to 3.2) for this study so that potential PIMs such as apatite (specific gravity = 3.16 to 3.22) and jarosite (specific gravity = 2.9 to 3.3) could be recovered. Mineral concentrates from the 0.25 to 0.5 mm fraction were described and characterized by ODM using a binocular microscope. A scanning electron microscope at ODM was used to identify minerals that could not be visually identified with confidence.

Quality assurance and quality control measures outlined in Spirito et al. (2011) were implemented for analytical determinations on till samples including the use of laboratory duplicates (approximately one duplicate sample per ten samples) and certified control standards from the Canada Centre for Mineral and Energy Technology (CANMET), approximately one standard sample per 30 samples. Both the laboratory duplicates and certified control standards were randomly inserted into the sample sequence. Following the protocols implemented at the GSC (Spirito et al., 2011; Plouffe et al., in press), spiked and blank samples were randomly inserted into the sample batch sent for indicator mineral processing to assess the quality of the processing circuit and the accuracy of mineral identification. In addition, field duplicate samples were collected to assess sediment heterogeneity (sample site variability).

ADDITIONAL PROJECT ACTIVITIES

A fundamental component of this project is 1:50 000 scale surficial geology mapping and interpretation of ice-flow history. This will be completed for each of the four study sites and is integral to characterizing the transport history and ultimately surface expression of dispersal from mineralized sources. These components are being undertaken through interpretation of aerial photographs and field observations.

A biogeochemical survey is also being conducted concurrently with the till mineralogy and geochemistry survey. Biogeochemistry has already proved to be a useful exploration tool in the Interior Plateau (cf., Hornbrook, 1970; Dunn, 1997; Dunn and Levson, 2010; Dunn and Anderson, 2011) and resultant data from this study will add to the growing body of knowledge on the uptake of commodity and pathfinder elements by coniferous trees. The outer bark of lodgepole pine (*Pinus contorta*) and Engelmann spruce (*Picea engelmannii*) were chosen as sample media for this biogeochemical survey (Fig. 5). To date, 487 biogeochemical samples have been collected from 309 sites (Fig. 2, 3). Ideally, outer bark samples are collected at each till sample site. Practically, this was not always possible as till samples were often collected in clear cuts and biogeochemical samples were occasionally collected over material types other than subglacial till including bedrock.

A significant contribution of this study will be a comparison between biogeochemical and till mineralogical and geochemical data collected at the same site, in the context of regional glacial dispersal from a known mineralized porphyry source. These comparisons may prove useful to mineral exploration companies working in areas with restricted till samples (i.e. due to a lack of appropriate sample material) but where tree species such as lodgepole pine or Engelmann spruce occur.

Figure 5. Collection of an Engelmann spruce (*Picea engelmannii*) bark sample as part of the biogeochemical survey in the Mount Polley study area. 2013-263

FUTURE WORK

An important contribution of this project will be the characterization of the ore and alteration mineralogy of each porphyry deposit and to compare this mineralogy to the till mineralogy. This will enable the identification of glacial dispersal of porphyry indicator minerals (PIMs) including abundance of minerals in till and distance of glacial transport taking into consideration bedrock source and ice-flow directions. The study will provide a clear indication of which PIMs survive glacial erosion, transport, and deposition in the subglacial environment, and subsequent weathering in the surficial environment, as well as potential modifications that could be made (if any) to the sample processing circuit to maximise recovery of minerals of interest.

Results will be published as new data are generated and interpreted. Project deliverables will culminate with the production of new surficial geology maps, interpreted ice-flow histories, and summary reports on PIMs in till, till matrix geochemistry, and biogeochemical data and interpretations.

SUMMARY

An integrated project which includes surficial geology mapping and identification of ice movement indicators, and collection of bedrock, till and tree bark samples for laboratory analyses has been developed around the Mount Polley, Gibraltar, Highland Valley, and Woodjam porphyry deposits. It seeks to further develop practical exploration methods and sampling protocols that are effective at identifying mineralization in glaciated terrains where bedrock outcrop is limited. The development of a robust protocol for the identification and characterization of PIMs for Cordilleran porphyry deposits will be a new and important outcome.

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