

Automated indicator-mineral analysis of the fine-sand, heavy-mineral concentrate fraction of till: a promising exploration tool for porphyry copper mineralization

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Abstract: Previous studies indicated that heavy mineralogy (specific gravity (SG) = 2.8–3.2 and >3.2) of the medium-sand fraction (0.25–0.50 mm) of till contains porphyry copper indicator minerals (PCIM) derived from mineralization or alteration zones. To improve the PCIM method for mineral exploration, we analyzed the heavy mineralogy (>3.2 SG) of the fine-sand fraction (0.125–0.180 mm) of till using an automated method that combines scanning electron microscopy (SEM) and mineral-liberation analysis (MLA). The MLA-SEM method identifies mineralogy based on grain composition determined by SEM–energy dispersive spectroscopy. The distributions of epidote and chalcopyrite in till at four porphyry copper deposits in British Columbia show similarities between the fine-sand fraction analyzed by MLA-SEM and the medium-sand fraction analyzed by optical mineralogy: both show dispersal parallel to ice-flow movements. Analyzing the fine-sand, heavy-mineral concentrate (HMC) fraction of till by MLA-SEM can be used in exploration for porphyry copper mineralization. We estimate 5 to 8 kg of bulk till is sufficient to prepare 0.3 g aliquots of fine-sand HMC for MLA-SEM; this is smaller than the 9 to 15 kg required for optical mineral analysis of the medium-sand HMC fraction. Smaller field samples can lower costs for reconnaissance mineral exploration.

Résumé : Des études antérieures ont indiqué que les minéraux lourds (densité = 2,8–3,2 et >3,2) dans la fraction du sable moyen (0,25–0,50 mm) du till renferment des minéraux indicateurs de minéralisation de cuivre porphyrique (MIMCP) qui proviennent des zones minéralisées ou des zones d'altération de ce type de minéralisation. Afin d'améliorer la méthode des MIMCP pour l'exploration minérale, nous avons analysé les minéraux lourds (densité >3,2) dans la fraction du sable fin (0,125–0,180 mm) du till en utilisant une méthode automatisée qui combine la microscopie électronique à balayage (MEB) et l'analyse de libération minérale (ALM). La méthode ALM-MEB permet d'identifier les minéraux d'après la composition des grains déterminée par la spectroscopie à dispersion d'énergie du microscope électronique à balayage. Les distributions de l'épidote et de la chalcopyrite dans le till aux environs de quatre gisements de cuivre porphyriques en Colombie-Britannique montrent des similitudes entre la fraction du sable fin analysée par ALM-MEB et la fraction du sable moyen analysée par minéralogie optique. Les deux méthodes montrent une dispersion parallèle aux directions de l'écoulement glaciaire. L'analyse de la fraction du sable fin des concentrés de minéraux lourds (CML) du till par ALM-MEB peut être utilisée pour la recherche de minéralisations de cuivre porphyriques. Nous estimons que 5 à 8 kg de till en vrac sont suffisants pour préparer 0,3 g d'aliquotes de sable fin des CML pour la méthode ALM-MEB, ce qui est beaucoup moins que les 9 à 15 kg nécessaires pour l'analyse des minéraux par microscopie optique de la fraction du sable moyen des CML. Le prélèvement d'échantillons plus petits sur le terrain peut entraîner une réduction des coûts pour l'exploration minérale de reconnaissance.

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INTRODUCTION

Porphyry copper deposits to be discovered in the Canadian Cordillera are unlikely to be ‘easy finds’, well exposed at surface. They will most likely be at depth, below the exposed bedrock or covered by glacial or other surficial sediments. Innovative and cost-effective mineral exploration methods will be required to find these buried deposits. As part of the Targeted Geoscience Initiative of the Geological Survey of Canada (GSC), researchers are developing mineral exploration methods based on the detection of minerals indicative of porphyry copper mineralization (termed porphyry copper indicator minerals (PCIMs)) in till and stream sediments (Hashmi et al., 2015; Plouffe and Ferbey, 2015, 2017; Plouffe et al., 2016; McClenaghan et al., 2018, 2019b, this volume; Beckett-Brown et al., 2019, this volume). This method relies on the optical identification of PCIM in the medium-sand, heavy-mineral concentrate (MSHMC) fraction of till (0.25–0.50 mm; 2.8–3.2 and >3.2 specific gravity (SG)). Certain ore (e.g. chalcopyrite, gold grains) and alteration (e.g. epidote, garnet) minerals define mineralogical anomalies in till dispersed by ice-flow movements and extending, in some cases, more than 10 km (Plouffe and Ferbey, 2017). Identifying PCIM in the MSHMC fraction of till is now considered an efficient approach to detect porphyry copper mineralization buried by glacial sediments.

To improve the PCIM method, we have investigated the mineralogy of the fine-sand, heavy-mineral concentrate (FSHMC) fraction (0.125–0.180 mm; >3.2 SG) of till using an automated method that combines a scanning electron microscope (SEM) and a mineral-liberation analysis (MLA) database with the energy dispersive fingerprints of minerals. We compare the abundance of two PCIMs in till (epidote and chalcopyrite) identified in the FSHMC fraction with the MLA-SEM, to the mineralogy of the MSHMC fraction determined by optical methods. We compare samples from four porphyry copper study sites in south-central British Columbia: Gibraltar, Highland Valley Copper, Mount Polley, and Woodjam. We show that the heavy minerals identified are similar in both size fractions and, as such, the fine-sand fraction of till provides valuable information in a mineral exploration program targeted at porphyry copper mineralization.

GEOLOGICAL SETTING AND PREVIOUS STUDIES

Our investigation of till mineralogy has benefited from archived samples collected as part of reconnaissance till-sampling surveys in the region of three porphyry copper deposits and one prospect in south-central British Columbia (Fig. 1): the Gibraltar porphyry Cu-Mo deposit (1 220 000 000 t of ore grading 0.3% Cu and 0.01% Mo; van Straaten et al., 2013; Taseko Mines Ltd., 2020); the Mount Polley porphyry Cu-Au±Ag deposit (150 000 000 t of ore grading 0.2 to 0.3% Cu and 0.2 to

0.3 g/t Au; Rees, 2013); the Highland Valley Copper porphyry Cu-Mo deposit (1 600 000 000 t of ore grading 0.4% Cu and 0.01% Mo; Byrne et al., 2013); and the Woodjam porphyry Cu-Au prospect (221 000 000 tonnes of ore grading 0.2 to 0.3% Cu and 0.3 to 0.5 g/t Au; Sherlock et al., 2013; Sherlock and Trueman, 2013). These deposits are hosted in felsic to intermediate Late Triassic to Early Jurassic intrusions of the Quesnel terrane, which is dominantly composed of the Nicola Group mafic volcanic and associated sedimentary rocks (Schiarizza, 2017). Field and laboratory methods along with till mineralogical and geochemical data produced as part of these surveys are presented in Ferbey et al. (2016) and Plouffe and Ferbey (2016).

Hashmi et al. (2015), Plouffe et al. (2016), and Plouffe and Ferbey (2017) interpreted the till composition data, taking into account ice-flow movements of the last glaciation. In short, three ice-movement events occurred at Gibraltar (in chronological order): 1) glaciers from local mountainous regions moved to the southeast, 2) coalescing valley glaciers derived from the Cariboo Mountains advanced to the southwest, and 3) a regional ice-flow movement to the northwest was derived from an ice divide located at approximately lat. 52°. Only the last two ice movements have affected the Woodjam and Mount Polley regions. The Highland Valley Copper deposits were only covered by south- to southeast-flowing ice derived from the ice divide at lat. 52°.

METHODS

Field methods for the regional till-sampling surveys completed at the four study sites are detailed in Ferbey et al. (2016) and Plouffe and Ferbey (2016). Till samples (9–15 kg) were processed for the optical identification of heavy minerals in the non-magnetic, 0.25 to 0.50 mm, 2.8 to 3.2, and greater than 3.2 SG fractions. The sample processing methodology is summarized in Figure 2a and in Plouffe and Ferbey (2015, 2016) and Ferbey et al. (2016). In these previous studies, the abundance of chalcopyrite is reported in the 0.25 to 0.50 mm, greater than 3.2 SG, and greater than 1.0 A and epidote is reported in the 0.25 to 0.50 mm, greater than 3.2 SG, and 0.8 to 1.0 A paramagnetic fraction (Fig. 2a). Here, we report the total abundance of epidote in the greater than 3.2 SG and 0.25 to 0.50 mm fraction prior to paramagnetic separation (Fig. 2a). Only a select number of samples at each study site were processed for total epidote abundance (Table 1; Appendix A); in other words, fewer 0.25 to 0.50 mm, greater than 3.2 SG samples were analyzed for total epidote abundance compared to chalcopyrite abundance. In the context of our study, the non-magnetic 0.25 to 0.50 mm and greater than 3.2 SG fraction is referred to as the MSHMC.

For our MLA-SEM study, we selected a limited number of samples from each study site that had been previously processed for PCIM in the MSHMC (Table 1) based on their location within and outside the PCIM dispersal trains

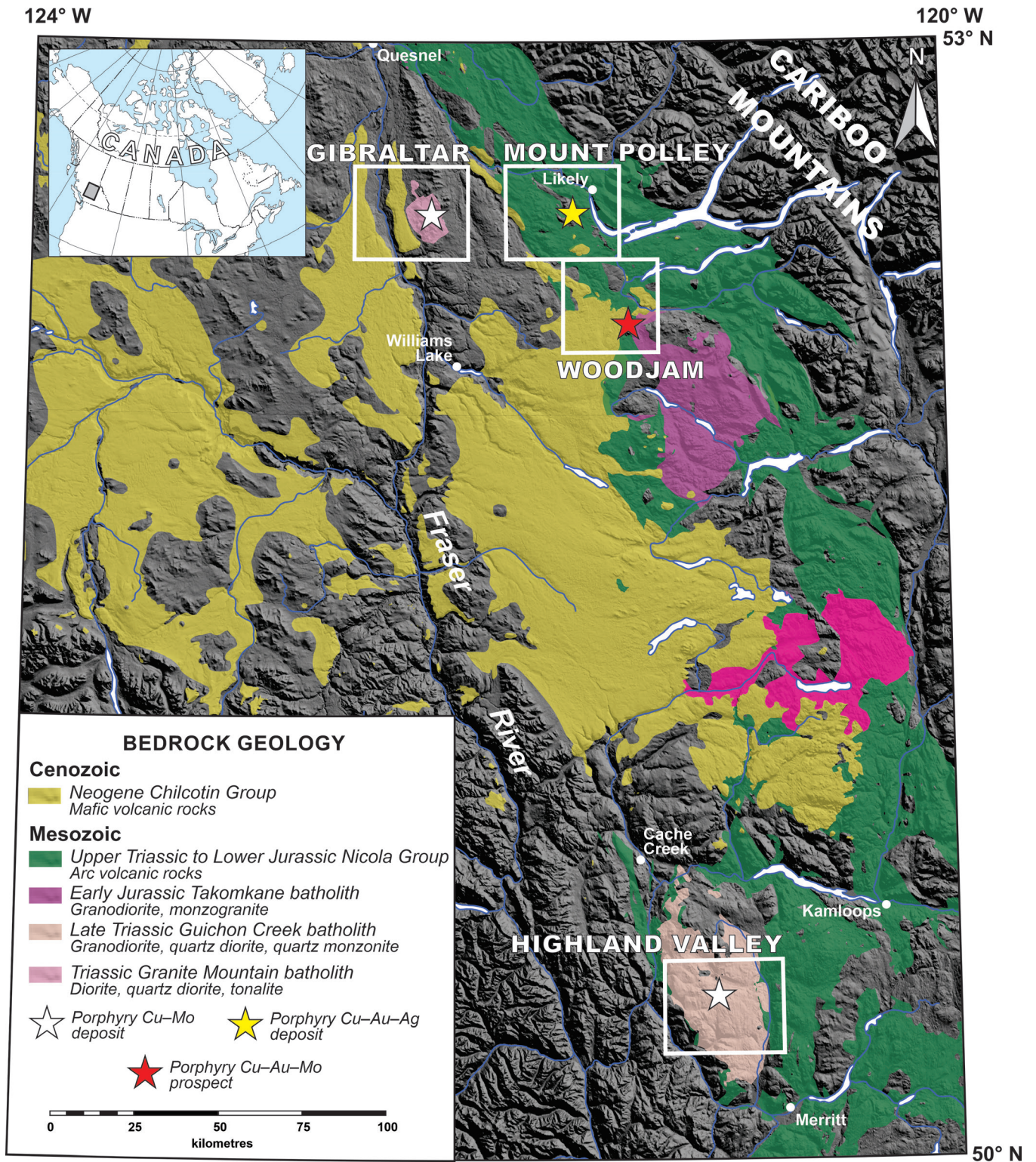


Figure 1. Location of the four porphyry copper study sites in British Columbia.

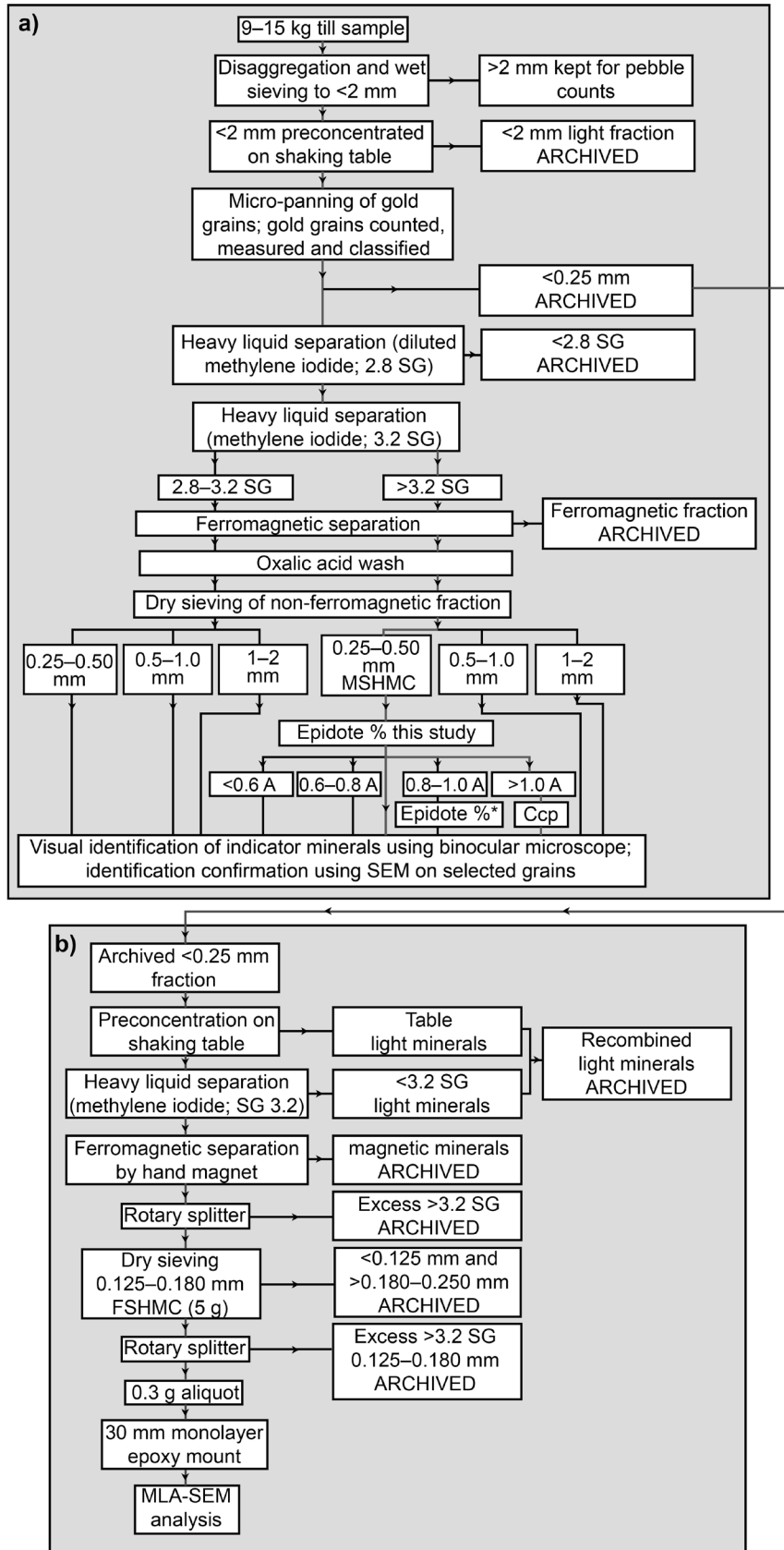


Figure 2. Flow charts representing: **a)** processing till samples for indicator minerals in the 0.25 to 2.00 mm size fraction (modified from Plouffe and Ferbey, 2016). Hashmi et al. (2015), Plouffe et al. (2016), and Plouffe and Ferbey (2017) reported the percentage of epidote in the 0.25 to 0.50 mm, greater than 3.2 specific gravity (SG), 0.8 to 1 A fraction, labelled 'Epidote %*'; we report epidote % in the 0.25 to 0.50 mm, greater than 3.2 SG fraction prior to paramagnetic separation, labelled 'Epidote % this study'; **b)** processing the less than 0.250 mm fraction to obtain a 0.125 to 0.180 mm fraction for mineral liberation analysis (MLA)—scanning electron microscopy (SEM).

FSHMC: Non-magnetic, fine-sand, heavy-mineral concentrate
 MSHMC: Non-magnetic, medium-sand, heavy-mineral concentrate
 Ccp: Chalcopyrite

Path for the processing of:
 MSMHC ———
 FSHMC ———

Table 1. Number of till samples processed for heavy mineral analysis in the 0.25 to 0.50 mm (Ferbey et al., 2016; Plouffe and Ferbey, 2016) and 0.125 to 0.180 mm size fractions (this study) of samples from four porphyry copper study sites in British Columbia.

Study site	0.25–0.50 mm Optical mineralogy (MSHMC)		0.125–0.180 mm MLA-SEM (FSHMC)
	Chalcopyrite	Epidote	Epidote and chalcopyrite
Highland Valley Copper	109	70	29
Gibraltar	96	50	20
Mount Polley	87	48	20
Woodjam	91	53	21

FSHMC: fine-sand, heavy-mineral concentrate; MLA-SEM: mineral-liberation analysis and scanning electron microscopy; MSHMC: medium-sand, heavy-mineral concentrate

outlined in Plouffe and Ferbey (2017); therefore, there are fewer MLA-SEM samples than MSHMC samples. The archived less than 0.250 mm fraction of these selected samples was reprocessed on the shaking table, concentrated in a heavy liquid (methylene iodide; 3.2 SG) and separated with a hand magnet to remove magnetic minerals at Overburden Drilling Management Ltd. (Ottawa, Ontario). The resulting less than 0.250 mm non-magnetic heavy mineral samples were passed through a rotary splitter to provide a representative split, which was dry sieved in the Sedimentology Laboratory at the GSC (Ottawa, Ontario) to obtain approximately 5 g of non-magnetic 0.125 to 0.180 mm, greater than 3.2 SG material (Fig. 2b), referred to in this paper as a fine sand heavy mineral concentrate (FSHMC). The sieves were cleaned between samples with Alconox® laboratory detergent in a sonic bath and rinsed with tap and distilled water. Grenier et al. (2015) did not find evidence of sample cross-contamination while using this sieve cleaning method. Sample loss during dry sieving is negligible, having been evaluated at 1.2% by Lougheed et al. (2019) after dry sieving heavy mineral concentrates (HMCs; <0.250 mm) of till.

Aliquots weighing approximately 0.3 g were obtained from each FSHMC sample using a rotary splitter, which produces homogeneous subsamples. These aliquots were mounted as a monolayer in a 30 mm diameter epoxy (Epofix resin) puck as described by Wilton and Winter (2012) and Wilton et al. (2017). Each mount contains up to 20 000 particles (Wilton et al., 2017). The monolayer mounting procedure eliminates preferential settling of heavy mineral grains in epoxy, which can result in over-representation of heavier minerals on the analyzed grain-mount surface (cf. Lougheed et al., 2018, 2020, this volume). The samples were polished using a Struers polishing system with a protocol for silicate minerals developed internally at Memorial University (MUN). All grain mounts were carbon-coated prior to MLA-SEM analyses. One grain mount was made per sample.

Following our method, only a portion of the FSHMC obtained from the original 9 to 15 kg samples was processed for MLA-SEM. In contrast, 100% of the MSHMC

was analyzed, as reported in Ferbey et al. (2016) and Plouffe and Ferbey (2016). As part of our research we evaluated if the 0.3 g aliquots used for MLA-SEM are representative of PCIM present in till as identified in the MSHMC.

The MLA-SEM system

The MLA-SEM facility in the Core Research Equipment and Instrument Training Network laboratories at MUN consists of a FEI Quanta 400 environmental SEM equipped with a dual Bruker energy dispersive spectroscopy (EDS) detector controlled by MLA software developed at the University of Queensland Julius Kruttschnitt Mineral Research Centre (JKTech) in Australia. The SEM was operated at a voltage of 25 kV and a beam current of 13 nA. The working distance between sample and detector was 12 mm and spot size was approximately 5 µm, representing the minimum detectable particle diameter. The imaging dwell time (i.e. time spent acquiring data) was 16 µs, with frame resolution of 800 pixels, and X-ray collection at 12 ms.

Mineral-liberation analysis software maps mineral particles based on their backscattered-electron (BSE) profiles; individual particles are defined based on subtle variations in the brightness of the BSE greyscale image, wherein minerals containing elements with greater atomic number are brighter (Fig. 3a). The MLA software controls full X-ray spectrum (EDS) analysis of each particle based on the distinct mapped brightness. The mineralogy of each particle is finally identified by the MLA software based on matching the energy dispersive X-ray signal from each particle in the grain mount to a database. False colour images of the grain mounts can be created to provide a visual overview of the distribution of the most abundant minerals (Fig. 3b).

For each analysis, the greyscale threshold was set with the epoxy as black (very low greyscale) and metallic copper as white (very high greyscale). The dwell time for each X-ray analysis of a particle was 60 µs. The MLA-SEM

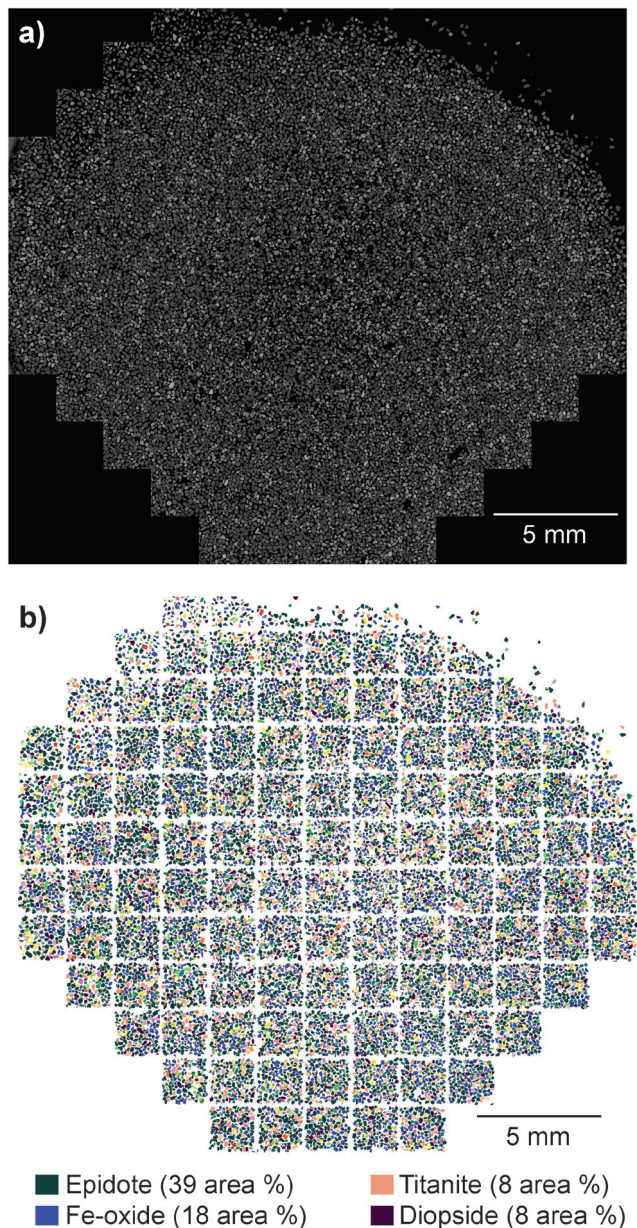


Figure 3. Example of **a)** a backscattered-electron image and **b)** a composite false colour image of a complete grain mount from sample 15PMA113A01 from the Highland Valley Copper study site, British Columbia. Only the most abundant minerals (≥ 8 area per cent) are shown in the legend.

analytical time was 45 to 60 min per sample and the post-processing time ranged from 10 to 30 min depending on the complexity of the sample.

The confidence level for matching individual spectra with the database was set at 90% during the initial analysis, where 100% is a perfect match and 50% is an average match. Following post-processing and identification of unknowns, the confidence level was reset to 70% for final calculation.

Following MLA-SEM analysis, each sample was post-processed on live SEM to evaluate any detected unknowns to ascertain whether each was truly an unidentified mineral or a defect in the polished surface (i.e. crack or hole). In rare cases, the analysis was obtained on the boundary between two minerals in a particle containing more than one mineral species and was, therefore, a mix of two mineral spectra. Higher resolution BSE images were obtained for a limited number of specific particles to better evaluate their mineralogy.

Non-mineral objects such as holes and parts of the grain mount were removed from the MLA-SEM maps. The final results include a list of the minerals in each sample reported as an area per cent of the total area of all minerals mapped in the sample. Through the MLA data processing, all minerals greater than 5 μm in size present in polymineral grains are identified as their respective mineral.

The SEM-EDS spot size of 5 μm corresponds to a circular particle with an area of 20 μm^2 (0.00002 mm^2). The 30 mm pucks used in our study were covered with FSHMC within a 25 mm diameter, corresponding to a total area of 491 mm^2 . Assuming 85% mineral grain coverage of this area, a 0.00002 mm^2 particle corresponds to $5 \times 10^{-6}\%$ or 0.000005% of the total area analyzed; consequently, we conservatively report the area per cent of chalcopyrite to five decimal places. Loughheed et al. (2020) calculated the analytical precision of mineral identification by MLA-SEM at less than ± 1 area per cent based on replicate analytical runs of identical sections with proper calibration measures between runs.

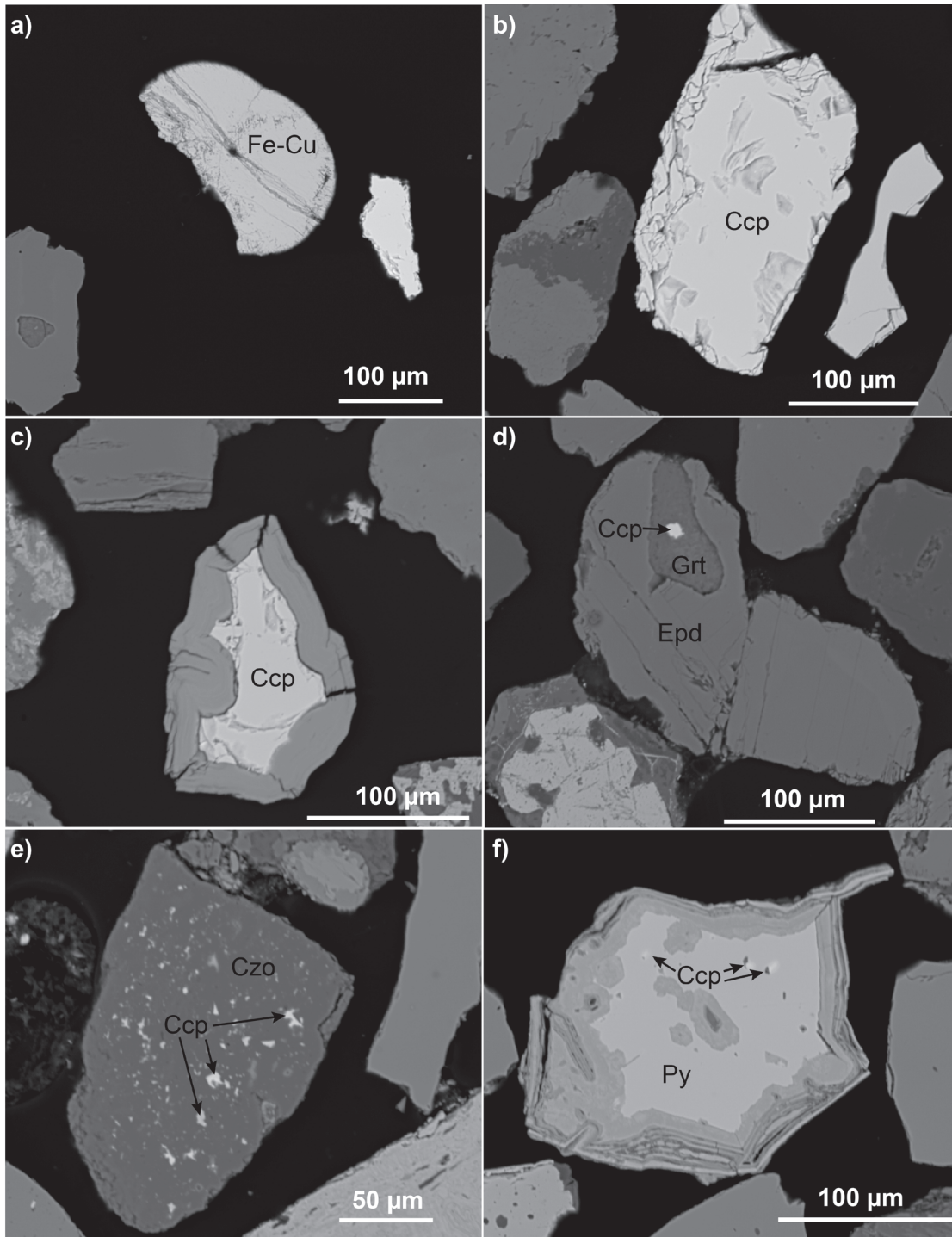
RESULTS

The full list of minerals obtained from the MLA-SEM analyses included a number of light minerals (e.g. albite, quartz, biotite) present in small percentages varying from 1.6 to 10.6 area per cent with an average of 4.8 area per cent (Table 2). These light minerals were present as part of polymineral grains with SG greater than 3.2. Light monomineral grains were detected in a few samples. We suspect that these grains were entrained with the heavy minerals during heavy mineral separation and attest to the technical difficulty of perfectly separating dense minerals from the fine-sand fraction. The Fe-oxide/hydroxide category includes the potential combination of hematite, goethite, limonite, and magnetite, which could only be differentiated with a longer analytical time than we applied. If magnetite was present, it occurred as a small percentage of polymineral grains, too small to have been removed during the magnetic separation. A small amount of contamination (average of 0.04%) in the form of brass and steel was detected in the samples (Fig. 4a). This contamination is most likely derived from field sampling tools (Plouffe et al., 2014; Lehtonen et al., 2015).

Table 2. Minimum, maximum, and average abundance of minerals identified by mineral-liberation analysis–scanning electron microscopy in the 0.125 to 0.180 mm heavy-mineral concentrate of samples of four porphyry copper study sites in British Columbia, presented as area per cent of the total area of all minerals mapped.

Minerals	Abundance (area %)			Minerals	Abundance (area %)		
	minimum	maximum	average		minimum	maximum	average
Aenigmatite	0.00	0.48	0.04	Ilmenite	0.01	13.28	3.34
Albite	0.16	2.12	0.82	Jagowerite	0.00	0.01	0.00
Allanite	0.00	0.64	0.00	Jarosite	0.00	0.02	0.00
Almandine	0.06	31.36	8.07	Leucosene	0.00	0.69	0.18
Al-Si oxides	0.00	2.47	0.44	Mn-oxides	0.00	0.25	0.01
Fine-grained alteration minerals (typically clay)	0.78	6.52	2.95	Monazite	0.00	0.06	0.01
Andradite	0.15	21.60	1.66	Muscovite	0.08	0.88	0.26
Anhydrite	0.00	0.01	0.00	Olivine	0.02	18.15	2.80
Apatite	0.01	4.47	0.65	Orthoclase	0.06	1.87	0.45
Astrophyllite	0.00	0.22	0.04	Orthopyroxene	0.00	27.26	2.11
Augite	0.20	4.25	0.77	Pentlandite	0.00	0.03	0.00
Barite	0.00	5.11	0.07	Perovskite	0.00	0.02	0.00
Biotite	0.03	0.55	0.15	Perthite	0.10	2.20	0.49
Bornite	0.00	0.43	0.00	Phlogopite	0.00	0.08	0.01
Brass and steel	0.00	0.27	0.04	Piemontite	0.00	0.29	0.02
Calcite	0.00	0.59	0.05	Plagioclase	0.09	3.72	1.01
Cassiterite	0.0000	0.0001	0.0000	Polymignyte	0.00	0.01	0.00
Chalcocite	0.00	0.80	0.01	Pyrite	0.00	7.10	0.16
Chalcopyrite	0.00	2.29	0.06	Pyrolusite	0.00	0.001	0.00
Chlorapatite	0.01	3.37	0.52	Pyrope	0.00	0.52	0.06
Chlorite	0.11	3.07	0.48	Pyrrhotite	0.00	6.78	0.64
Chromite	0.00	0.49	0.07	Quartz	0.00	4.89	1.36
Copper, native	0.00	0.01	0.00	Rutile	0.02	4.05	1.24
Cordierite	0.00	0.05	0.01	Scapolite	0.01	0.55	0.12
Coronadite	0.00	0.05	0.00	Scheelite	0.00	0.02	0.00
Corundum	0.00	0.03	0.01	Serpentine	0.00	0.12	0.01
Covellite	0.00	0.004	0.00	Siderite	0.00	0.43	0.04
Diopside	0.88	93.41	25.35	Spessartine	0.00	1.78	0.11
Dolomite	0.00	0.06	0.00	Sphalerite	0.00	0.01	0.00
Epidote	0.07	49.42	17.78	Spinel	0.00	0.50	0.05
Fe-oxide/hydroxide	0.23	41.47	11.37	Staurolite	0.00	5.83	1.41
Florencite-(Ce)	0.00	0.02	0.00	Sulfide-oxide	0.00	3.24	0.64
Fluorite	0.00	0.003	0.00	Thorite	0.00	0.10	0.00
Fuchsite	0.00	0.89	0.12	Titanite	0.02	21.39	3.88
Gahnite	0.00	0.50	0.00	Topaz	0.00	0.14	0.04
Galena	0.000	0.001	0.000	Tourmaline	0.01	1.09	0.22
Grossular	0.00	7.56	0.36	Wollastonite	0.00	0.06	0.01
Hedenbergite	0.00	0.20	0.02	Xenotime	0.00	0.02	0.00
Hercynite	0.00	0.09	0.01	Zircon	0.00	3.52	0.58
Hornblende	0.47	14.93	5.58	Zoisite	0.00	3.31	1.09

Minerals in bold italic are light minerals (<3.2 specific gravity)



Ccp: chalcopyrite; Czo: clinozoisite; Epd: epidote; Fe-Cu: iron-copper contaminant; Grt: garnet; Py: pyrite

Figure 4. Backscattered-electron images of the fine-sand, heavy-mineral concentrate of till samples from porphyry copper study sites in British Columbia: **a)** Fe-Cu contaminant in sample 11PMA024A01 from Gibraltar; **b)** discrete unoxidized chalcopyrite grain in sample 11PMA024A01 from Gibraltar; **c)** partly oxidized chalcopyrite grain in sample 15PMA112A01 from Highland Valley Copper; **d)** chalcopyrite in garnet in epidote in sample 12PMA585A01 from Mount Polley; **e)** abundant chalcopyrite inclusions in clinozoisite (aluminium-rich epidote) in sample 12TFE047A01 from Gibraltar; and **f)** chalcopyrite inclusions in partly oxidized pyrite in sample 12TFE126A01 from Woodjam.

The most abundant minerals identified by MLA-SEM include clinopyroxene (diopside), epidote, and Fe-oxide/hydroxide. Titanite was found in large percentages (>15%) in a limited number of samples. These minerals were also the main constituents of the till MSHMC (Ferbey et al., 2016; Plouffe and Ferbey, 2016). We interpret the clinopyroxene to be derived from the mafic volcanic rocks of the Quesnel terrane, including Nicola Group and Chilcotin Group basalts (Schiarizza, 2016). Titanite is interpreted to be derived from intrusive rocks, including the batholiths that host the porphyry mineralization (Bouzari et al., 2011; Celis, 2015; Kobylinski et al., 2020). Epidote is derived dominantly from two sources: the hydrothermal alteration zones related to porphyry mineralization and the metamorphosed Nicola Group rocks (Plouffe et al., this volume).

We present the distribution patterns of two PCIMs identified in till: 1) chalcopryite, an ore mineral, and 2) epidote, a mineral present in the alteration zones associated with porphyry mineralization. The distributions of chalcopryite in the MSHMCs were previously described by Hashmi et al. (2015), Plouffe et al. (2016), and Plouffe and Ferbey (2017) and are only summarized here. At the four study sites, chalcopryite, the main copper-ore mineral, is more abundant in till MSHMC near and down-ice of economic and subeconomic mineralization than it is regionally (Fig. 5a, 6a, 7a, and 8a). At Gibraltar, chalcopryite in till follows an amoeboid dispersal pattern controlled by the three phases of ice-flow movement, which eroded a cluster of economic and subeconomic porphyry copper mineralized zones (Fig. 5a). At Mount Polley and Highland Valley Copper, glacial dispersal of chalcopryite extends more than 10 km parallel to the dominant ice-flow movement: to the northwest at Mount Polley and south-southeast at Highland Valley Copper (Fig. 6a, 7a). At Woodjam, chalcopryite dispersal in till extends approximately 2 km southwest and northwest from the mineralized zones, that is, parallel to both ice movements (Fig. 8a).

Regional glacial dispersal based on FSHMC of till cannot be assessed with the same level of detail as was determined using MSHMC given the smaller number of FSHMC samples (Table 1); however, chalcopryite distribution in the FSHMC of till shows greater abundance near mineralization compared to its regional distribution at Gibraltar, Highland Valley Copper, and Woodjam (Fig. 5b, 7b, and 8b), which we interpret as being derived from porphyry copper occurrences. Chalcopryite occurs as discrete grains and as inclusions in other minerals (Fig. 4). At Mount Polley, chalcopryite in the MSHMC is most abundant near and down-ice of mineralization; this is not the case in the FSHMC (Fig. 6a, b). This could result from chalcopryite being less abundant in the fine sand fraction compared to the medium sand fraction of till at that site. Also, the aliquot weight (0.3 g), despite containing approximately 20 000 grains, might be insufficient to represent the abundance of chalcopryite in the FSHMC at that site. We estimate that the chalcopryite area per cent in the FSHMC linked to mineralization is equivalent to greater

than 0.02459 area per cent at Gibraltar, greater than 0.00922 area per cent at Woodjam, and greater than 0.07984 area per cent at Highland Valley (Fig. 5b, 7b, and 8b). In other words, the chalcopryite area per cent threshold value in the FSHMC varies between the four study sites, which is likely related to the extent and grade of mineralization exposed to glacial erosion, as was suggested by Plouffe et al. (2016) in their interpretation of the chalcopryite abundance in the MSHMC.

At the four study sites, pale green to pistachio green epidote in the MSHMC of till is more abundant in samples near and down-ice from porphyry mineralization and associated alteration zones compared to samples from surrounding areas barren of mineralization (Fig. 5c, 6c, 7c, and 8c). The dispersal patterns of total epidote abundances in the MSHMC reported here are similar to those presented by Hashmi et al. (2015), Plouffe et al. (2016), and Plouffe and Ferbey (2017) based on the abundance of epidote in the 0.8 to 1.0 A fraction of the MSHMC. At Gibraltar, till samples with greater than 45% epidote in the MSHMC occur across a minimum distance of 26 km north to south and 9 km east to west, centred on the Granite Mountain batholith, which is known to contain hydrothermal alteration epidote as far as 10 km from the ore zones (Fig. 5c; Ash and Riveros, 2001; van Straaten et al., 2013; Kobylinski et al., 2017, 2020). Epidote abundance greater than 45% in till north of the Granite Mountain batholith likely results from glacial dispersal; however, greater than 45% epidote in till south of the Granite Mountain batholith is likely derived from a combination of southeastward glacial transport in the early phase of glaciation and the underlying Early Cretaceous intrusive bedrock (Sheridan stock), which is known to contain hydrothermal alteration epidote (Ash and Riveros, 2001). At Mount Polley, greater than 7% epidote in the MSHMC of till defines a dispersal train extending 3 km southwest of the intrusion parallel to the first phase of ice flow and down-ice from the alteration zones with epidote (Fig. 6c; Rees, 2013). At Highland Valley, till samples with greater than 39% epidote are heterogeneously distributed along and down ice of the Highland Valley fault, where sodic-calcic and propylitic alteration characterized by epidote veins was mapped over a 34 km² area centred on mineralization (Fig. 7c; Casselman et al., 1995; Lesage et al., 2016; Byrne et al., 2020a, b). The source of 70% epidote in the MSHMC of one till sample collected in the northwest of the Guichon Creek batholith, is uncertain; it is most likely derived from propylitic alteration associated with subeconomic porphyry copper mineralization in that region (British Columbia Geological Survey, 2020). Similarly, the source of epidote (60% of the MSHMC) in one till sample at the southern limit of sampling is uncertain; it is most likely derived from alteration zones associated with porphyry copper mineral occurrences, potentially along the Lornex fault, up-ice from the sampling site. Lastly, at Woodjam, till samples with greater than 25% epidote are all located within 1.5 km of the mineralized zones where propylitic alteration with epidote is reported (Fig. 8c; Sherlock and Trueman, 2013; Sherlock et al., 2013).

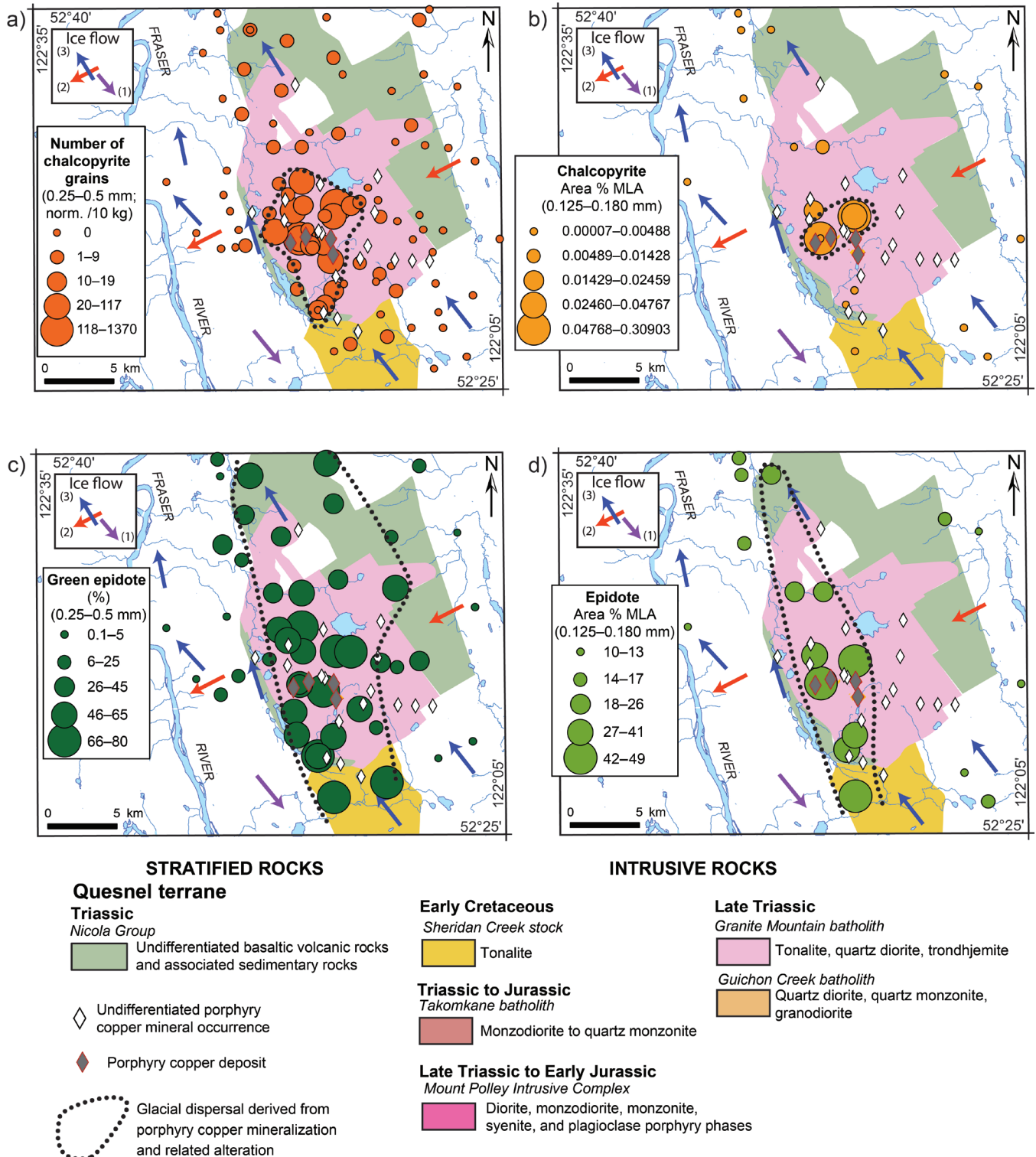


Figure 5. Till mineralogy in the region of the Gibraltar porphyry copper-molybdenum deposit, British Columbia: **a)** chalcopyrite grain counts in the medium-sand, heavy-mineral concentrate (MSHMC) normalized to a 10 kg bulk sample (*modified from* Plouffe et al., 2016 and Plouffe and Ferbey, 2017); **b)** chalcopyrite area per cent in the fine-sand, heavy-mineral concentrate (FSHMC) as determined by mineral-liberation analysis (MLA)–scanning electron microscopy (SEM); **c)** epidote percentages in the MSHMC, and **d)** epidote area per cent in the FSHMC as determined by MLA-SEM. Simplified bedrock geology *after* Massey et al. (2005) and Schiarizza (2015).

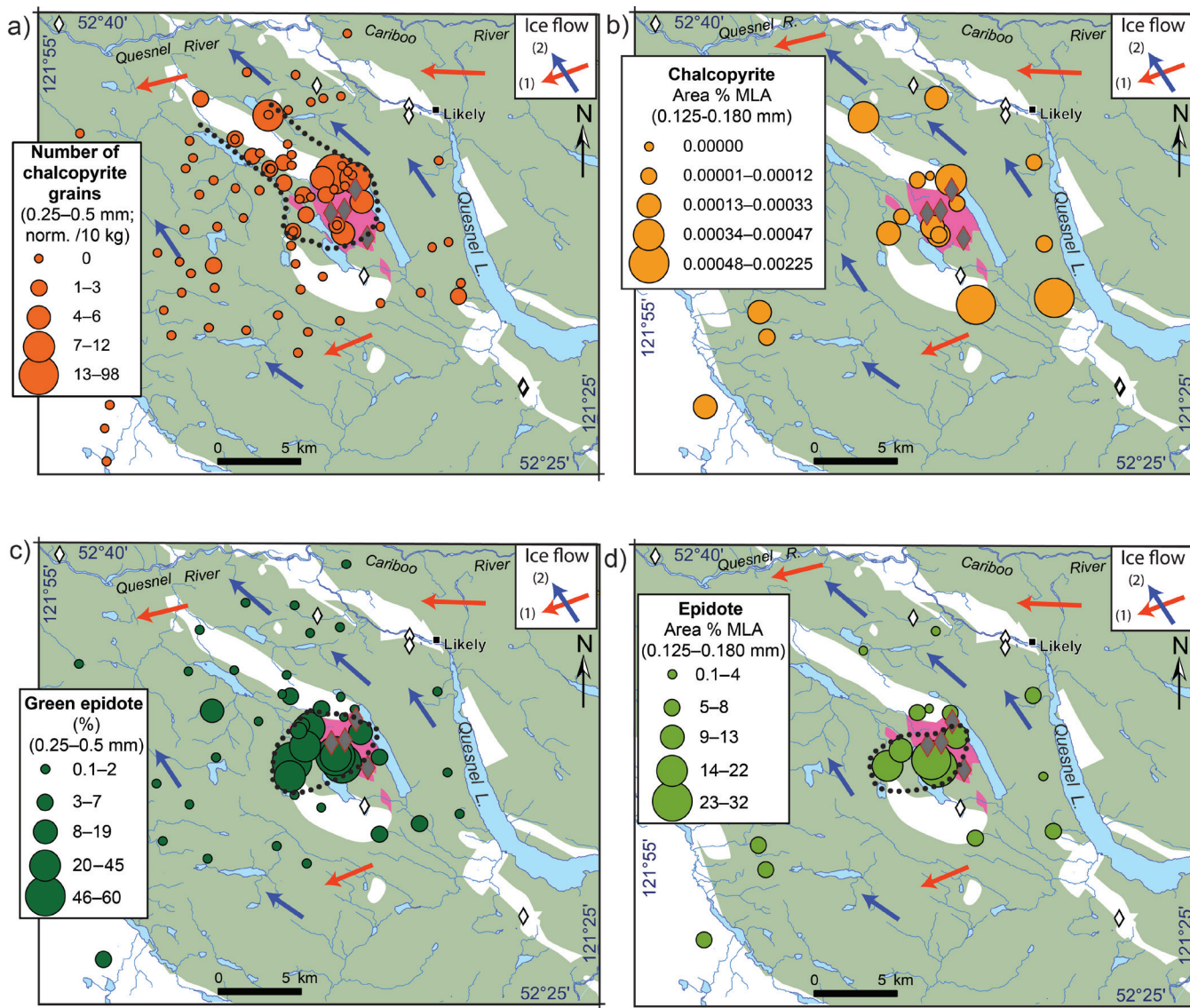


Figure 6. Till mineralogy in the region of the Mount Polley porphyry copper-gold deposit, British Columbia: **a)** chalcopyrite grain counts in the medium-sand, heavy-mineral concentrate (MSHMC) normalized to 10 kg bulk sample (*modified from* Hashmi et al., 2015; Plouffe et al., 2016; and Plouffe and Ferbey, 2017); **b)** chalcopyrite area per cent in the fine-sand, heavy-mineral concentrate (FSHMC) as determined by mineral-liberation analysis (MLA)–scanning electron microscopy (SEM); **c)** epidote percentages in the MSHMC, and **d)** epidote area per cent in the FSHMC as determined by MLA-SEM. See Figure 5 for bedrock geology legend. Simplified bedrock geology *after* Massey et al. (2005) and Rees (2013).

Although the number of FSHMC samples processed by MLA-SEM is less than the number of MSHMC samples, epidote distribution patterns in both size fractions show similarities (Fig. 5d, 6d, 7d, and 8d). At Gibraltar, samples with greater than 17 area per cent epidote in the FSHMC follow a north-south extent over a minimum distance of 26 km, similar to the distribution of greater than 45% epidote in the MSHMC (Fig. 5d). Samples with greater than 17 area per cent epidote in the FSHMC to the north-northwest of mineralization result from glacial transport. At Mount Polley, samples with greater than 8 area per cent epidote are located above the Mount Polley Intrusive Complex or 3 km to the

southwest, parallel to the first phase of ice flow (Fig. 6d). At Highland Valley, samples with greater than 10 area per cent epidote are located close to or down-ice (south) from the Highland Valley fault, except for one sample in the north-west, which contains 19 area per cent epidote in the FSHMC and 70% epidote in the MSHMC (Fig. 7d). At Woodjam, samples with greater than 16 area per cent epidote are located within 1.5 km of the main mineralized zones (Fig. 8d). Just as Hashmi et al. (2015), Plouffe et al. (2016), and Plouffe and Ferbey (2017) concluded, we interpret the greater abundance of epidote in till near porphyry copper mineralization as being derived from the associated propylitic alteration

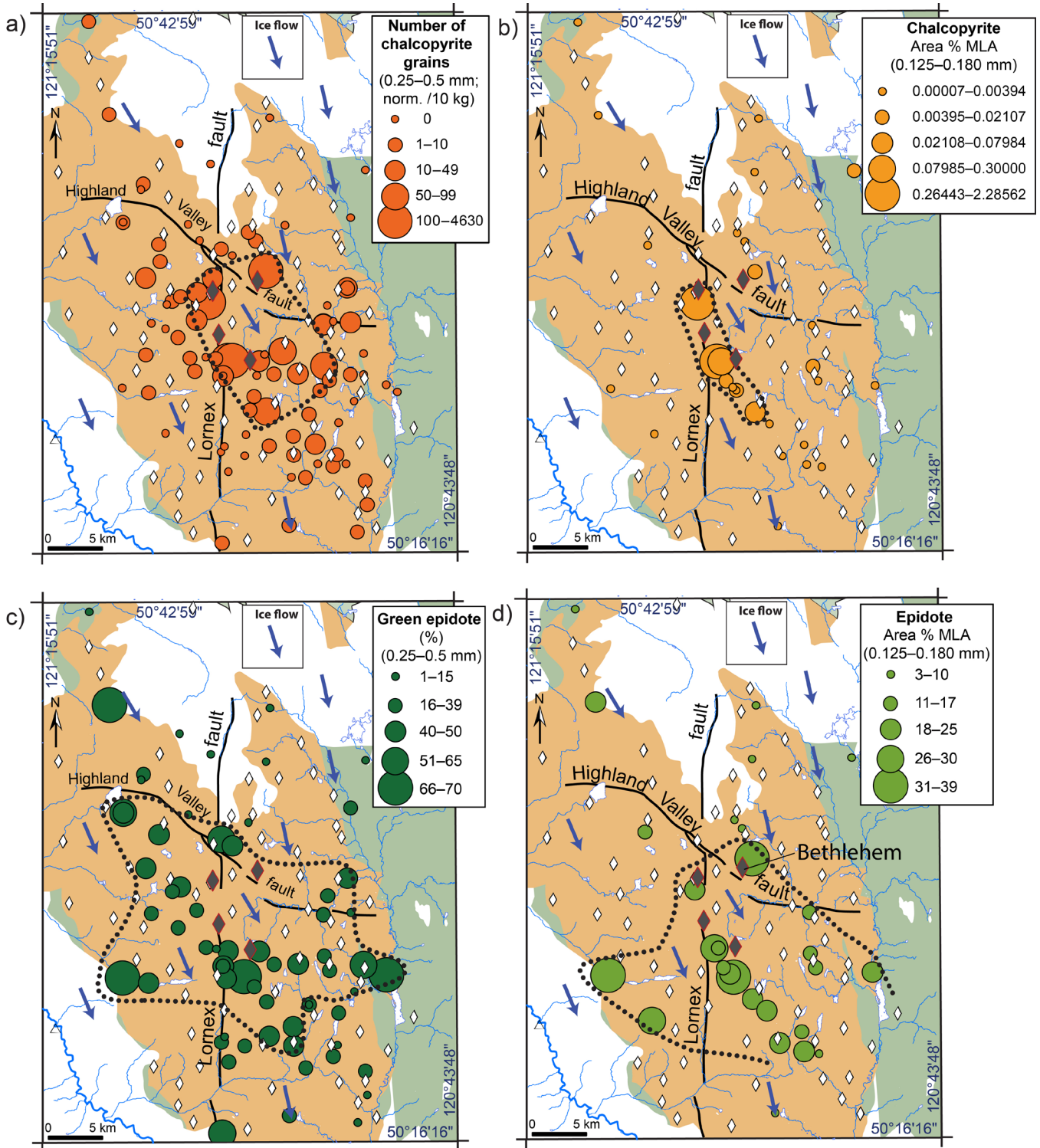


Figure 7. Till mineralogy in the region of the Highland Valley Copper porphyry copper-molybdenum deposit, British Columbia: **a)** chalcopyrite grain counts in the medium-sand, heavy-mineral concentrate (MSHMC) normalized to a 10 kg bulk sample (*modified from* Plouffe and Ferbey, 2017); **b)** chalcopyrite area per cent in the fine-sand, heavy-mineral concentrate (FSHMC) as determined by mineral-liberation analysis (MLA)–scanning electron microscopy (SEM); **c)** epidote percentages in the MSHMC, and **d)** epidote area per cent in the FSHMC as determined by MLA-SEM. See Figure 5 for bedrock geology legend. Simplified bedrock geology after McMillan et al. (2009).

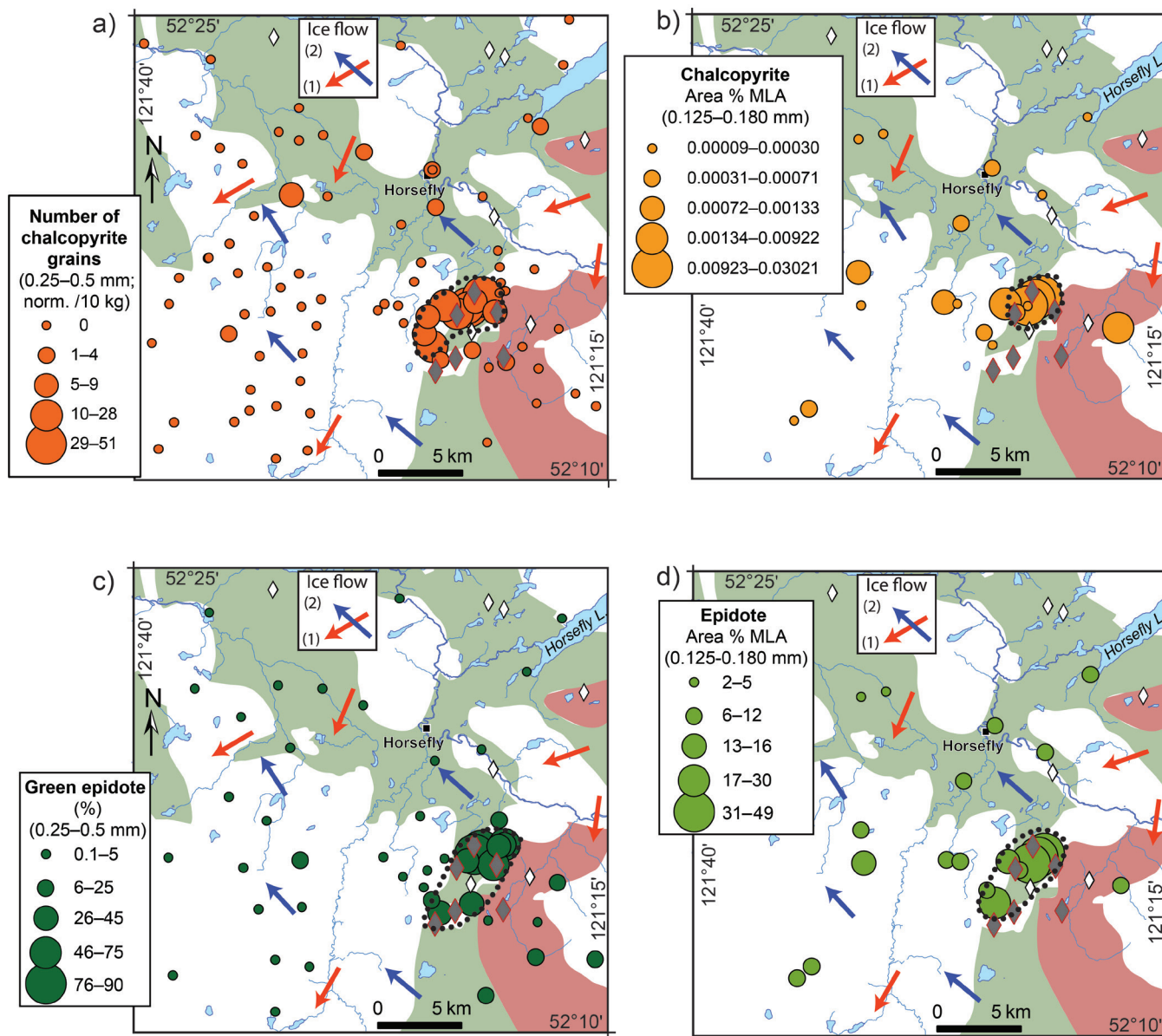


Figure 8. Till mineralogy in the region of the Woodjam porphyry copper-gold prospect, British Columbia: **a)** chalcopyrite grain counts in the medium-sand, heavy-mineral concentrate (MSHMC) normalized to a 10 kg bulk sample (*modified from* Plouffe et al., 2016; Plouffe and Ferbey, 2017); **b)** chalcopyrite area per cent in the fine-sand, heavy-mineral concentrate (FSHMC) as determined by mineral liberation analysis (MLA)–scanning electron microscopy (SEM); **c)** epidote percentages in the MSHMC, and **d)** epidote area per cent in the FSHMC as determined by MLA-SEM. See Figure 5 for bedrock geology legend. Simplified bedrock geology *after* Massey et al. (2005) and Logan et al. (2010).

zones. This interpretation is also supported by Plouffe et al. (this volume), who conclude based on epidote chemistry that a large amount of epidote in till at Gibraltar, Mount Polley, and Woodjam was derived from hydrothermal alteration associated with porphyry copper mineralization.

DISCUSSION

Previous studies report the successful application of MLA-SEM or other SEM-based automated mineral identification methods to mineral exploration in the Canadian Cordillera and elsewhere in Canada. Mackay et al. (2016) and Simandl et al. (2017) presented a two-step approach combining portable XRF and a quantitative evaluation of minerals by scanning electron microscopy (QEMSCAN[®]) from a commercial laboratory to detect carbonatite indicator minerals in stream sediments. They reported the detection of minerals of the pyrochlore supergroup and the columbite-tantalite series, and rare-earth element (REE)–fluorocarbonates and monazite in the 0.125 to 0.250 mm fraction of stream sediments draining carbonatites at three study sites: Alley, Lonnie, and Wicheeda. They identified these minerals in the 0.125 to 0.250 mm fraction of heavy concentrates produced with a Mozley C800 table and the non-concentrate of the same size fraction.

In another study based on MLA-SEM analysis of the less than 0.250 mm and greater than 3.2 SG fraction of four till samples at each of the Izok Lake volcanogenic massive sulfide deposit in the Northwest Territories and the Sisson granite-hosted W-Mo deposit in New Brunswick, Loughheed et al. (2020, this volume) conclude that ore (e.g. chalcopyrite, galena, sphalerite, scheelite, wolframite, Bi minerals) and alteration minerals (e.g. gahnite, corundum, epidote) can be identified in till up to 8 km down-ice from mineralization at Izok Lake and 10 km down-ice at Sisson, in both cases further extending the glacial dispersal identified from the 0.25 to 0.50 mm, greater than 3.2 SG mineralogy. They show that the greater than 3.2 SG, 0.125 to 0.250 mm fraction is optimal for MLA-SEM analysis.

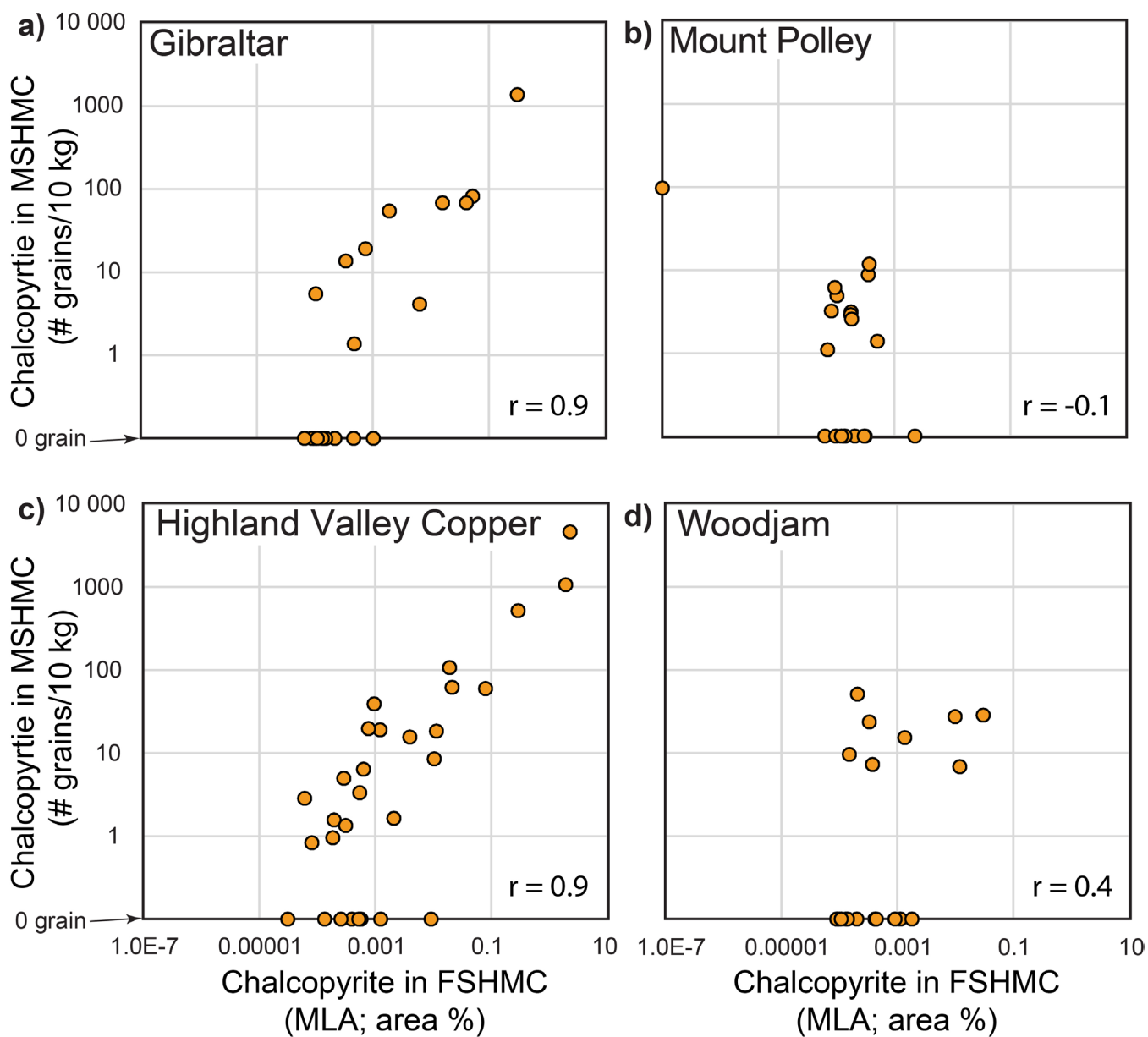
In a research project testing the use of MLA-SEM for the mineral exploration of nickel deposits associated with serpentinized ophiolites, Wilton and Winter (2012) and Wilton et al. (2017) identified awaruite, a Ni-Fe alloy, and asbolane and pecoraite (two hydrated nickel-bearing minerals) in stream sediments and till from Newfoundland. These minerals were detected in the 0.125 to 0.180 mm fraction of till and stream sediments concentrated with a Wilfley shaking table (Wilton and Winter, 2012).

Lastly, McClenaghan et al. (2019a) presented the results from the MLA-SEM examination of one gossan and one till sample from the Cu–Ni–platinum-group elements–Au Broken Hammer deposit in the North Range of the Sudbury structure, Ontario. Analyses of five size fractions (0.180 to 0.250, 0.125 to 0.180, 0.075 to 0.125, 0.045 to 0.075, and <0.045 mm) concentrated with a hydroseparator are

reported. In both the gossan and till samples, MLA-SEM reveals the presence of the same ore minerals identified by optical mineralogy (e.g. sperrylite, gold, and chalcopyrite) and additional minerals unrecognized optically (e.g. cassiterite, arsenopyrite, pentlandite, pyrrhotite, and galena). Chalcopyrite and pyrite in the till sample are dominantly present in the 0.125 to 0.250 mm heavy fraction.

Together, these results indicate the effectiveness of MLA-SEM at identifying minerals in the fine (<0.250 mm) fraction of detrital sediments and thus its direct application to mineral exploration.

Our study is the first to describe and compare the regional distributions of minerals identified by MLA-SEM in the FSHMC of till to the mineralogy identified optically in the MSHMC of samples from regions of porphyry mineralization. Even with a limited number of samples, the abundance of ore (chalcopyrite) and alteration (epidote) minerals identified in the FSHMC by MLA-SEM reflects the presence of porphyry copper mineralization with a greater abundance of these minerals in till near mineralization and associated alteration zones compared to regions barren of mineralization (Fig. 5b, 5d, 6d, 7b, 7d, 8b, and 8d), with the exception of chalcopyrite abundances at Mount Polley (Fig. 6b). Correlations in the abundance of chalcopyrite and epidote in the FSHMC and MSHMC can be illustrated geographically (Fig. 5–8), but also graphically (Fig. 9, 10). Chalcopyrite abundance generally correlates well between both size fractions at Gibraltar and Highland Valley Copper (Fig. 9a, c). The strong correlation is confirmed with Pearson correlation coefficients of 0.9 in both cases. We selected the Pearson method to calculate the correlation coefficients because it applies to data sets that include a number of observations with a value of zero (Huson, 2007). There is no obvious correlation between chalcopyrite in the FSHMC and the MSHMCs at Mount Polley and Woodjam (Fig. 9b, d). In this case, the Pearson correlation coefficient is –0.1 for Mount Polley and 0.4 for Woodjam. As mentioned above, the poor correlation between chalcopyrite abundance in the FSHMC and the MSHMC at Mount Polley could be related to the low abundance of this mineral in the FSHMC of till at the site. At Woodjam, although samples with the greatest abundance of chalcopyrite in the FSHMC and the MSHMC are all located near porphyry copper mineralization (Fig. 7b), the low correlation between the chalcopyrite content of both size fractions ($r = 0.4$) is likely related to the heterogeneous distribution of this mineral in till. At all sites, there are samples for which chalcopyrite was identified in the FSHMC and not in the MSHMC, probably because it is only present as discrete particles less than 0.250 mm in size or as inclusions within other minerals (Fig. 4d, e, f). The abundance of epidote in the FSHMC and MSHMC generally correlates better than for chalcopyrite at all study sites, with Pearson correlation coefficients of 0.8 at Gibraltar, 0.9 at Mount Polley, 0.8 at Highland Valley Copper, and 0.9 at Woodjam (Fig. 10). At Mount Polley and Woodjam, a few samples only contain epidote in the FSHMC (Fig. 10b, d). Based on



r = Pearson correlation coefficient

Figure 9. Correlation graph between the numbers of chalcopyrite grains normalized to a 10 kg bulk sample in the medium-sand, heavy-mineral concentrate (MSHMC) and the area per cent of chalcopyrite determined by mineral-liberation analysis (MLA)–scanning electron microscopy (SEM) in the fine-sand, heavy-mineral concentrate (FSHMC) of till at: **a)** Gibraltar, **b)** Mount Polley, **c)** Highland Valley Copper, and **d)** Woodjam porphyry study sites.

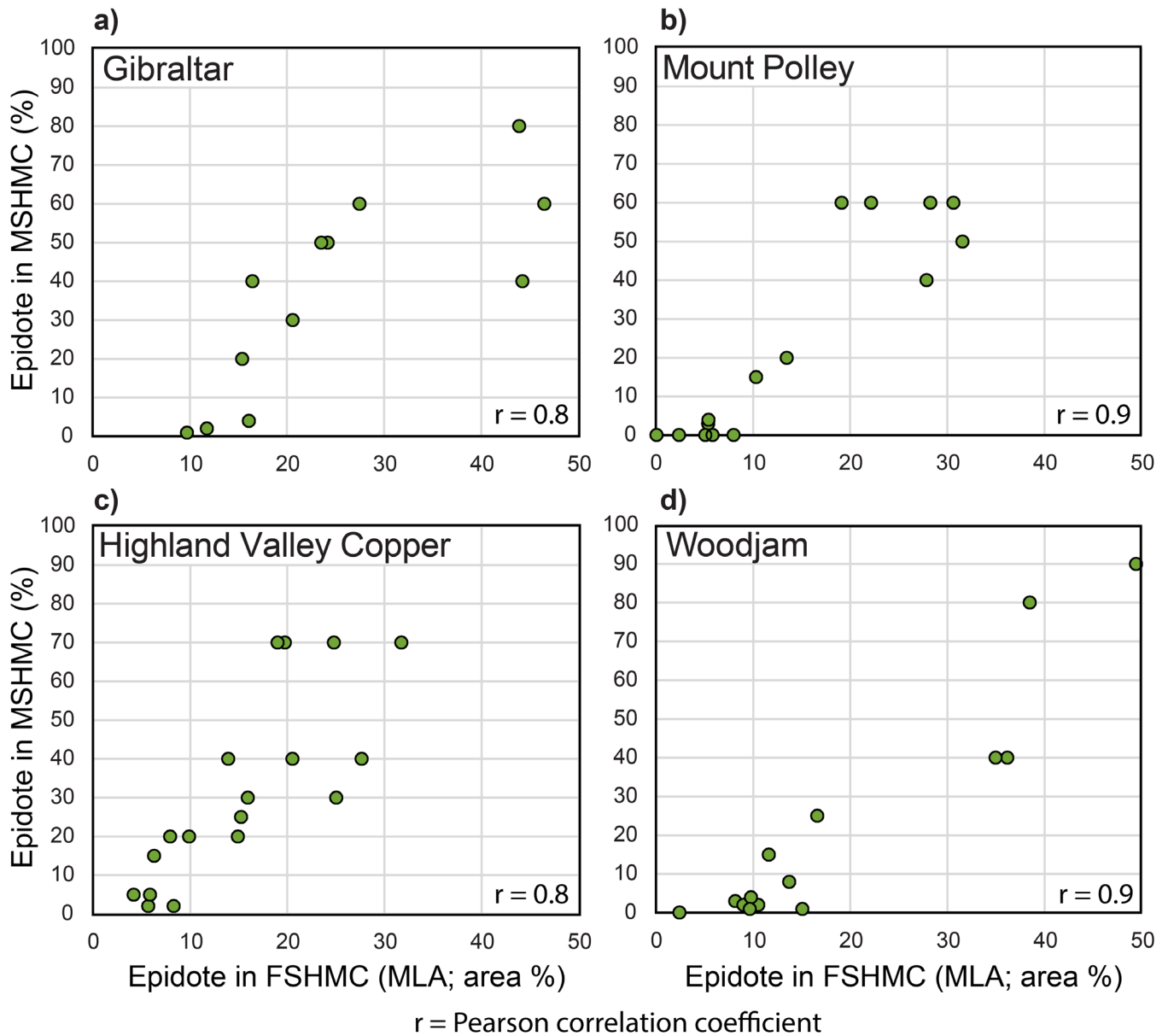


Figure 10. Correlation graph between the percentage of epidote in the medium-sand, heavy-mineral concentrate (MSHMC) and the area per cent of epidote determined by mineral-liberation analysis (MLA)-scanning electron microscopy (SEM) in the fine-sand, heavy-mineral concentrate (FSHMC) of till at: **a)** Gibraltar, **b)** Mount Polley, **c)** Highland Valley Copper, and **d)** Woodjam porphyry study sites.

the comparison of the mineralogy between the MSHMC and the FSHMC and the greater abundance of ore and alteration minerals near mineralization compared to the background region with no mineralization, we conclude that the mineralogy of the FSHMC of till determined by MLA-SEM provides an indication of porphyry copper mineralization.

The aliquot weight (0.3 g) used for MLA-SEM was sufficient to identify in till evidence of copper mineralization and/or associated alteration at the four study sites. The requirement of small aliquots (0.3 g) for MLA-SEM is an advantage because it only requires a small bulk-till sample. Based on the abundance of less than 0.250 mm material

from till samples (Ferbey et al., 2016; Plouffe and Ferbey, 2016), we estimate that 5 to 8 kg of bulk till is sufficient to prepare 0.3 g aliquots for MLA-SEM of the FSHMC. This is smaller than the typical 9 to 15 kg bulk-till sample weight required for optical mineralogy analysis of the MSHMC. The required bulk-till sample weight for MLA-SEM will vary depending on till texture, but smaller sample sizes are faster to collect in the field and are less expensive to ship and process for heavy mineral separation, as Lehtonen et al. (2015) also pointed out. Smaller samples (5–8 kg instead of 9–15 kg) could be collected as part of a reconnaissance till-sampling survey. Follow-up till sampling with larger

samples (9–15 kg) could be pursued in regions with anomalous results and processing them for the geochemistry of the till matrix (<0.063 mm or <0.002 mm) and identification of PCIM in the FSHMC and MSHMC. Using such an approach, even the porphyry copper mineralization would have been detected in a reconnaissance phase at Mount Polley because there was a copper anomaly defined from the till geochemistry at that site (Plouffe et al., 2016).

In their study of epidote in the alteration zones associated with porphyry copper mineralization and in the metamorphosed Nicola Group mafic volcanic rocks, Plouffe et al. (2019, this volume) show that metamorphic epidote is generally fine grained and less than 0.250 mm in size, suggesting that the FSHMC could potentially include more metamorphic epidote unrelated to porphyry copper mineralization compared to MSHMC; however, our results indicate that even with the potential ‘contamination’ with metamorphic epidote, the abundance of this mineral in the FSHMC can be correlated with the presence of alteration associated with porphyry copper mineralization (Fig. 5d, 6d, 7d, and 8d).

Previous research has shown that, MLA-SEM and other SEM-based mineral identification techniques (e.g. QEMSCAN®; cf. Layton-Matthews et al., 2017) can provide benefits over the traditional optical identification of minerals in detrital sediments (Wilton and Winter, 2012; Mackay et al., 2016; Layton-Matthews et al., 2017; Simandl et al., 2017; Wilton et al., 2017; Loughheed et al., 2020, this volume), including

- once a mineral library is developed or obtained from services offered at a commercial laboratory, mineral identification is not operator dependent and is based on mineral composition (i.e. no inherent bias from human observation);
- minerals present as discrete grains less than 0.250 mm, as inclusions greater than 0.000020 mm² (2 μm²), or as constituents of polymineral grains are identified;
- SEM images generated during MLA provide details of internal mineral zonation and texture;
- the abundance of major mineral constituents are precisely determined based on mineral composition as opposed to being estimated from the optical evaluation in a greater than 0.250 mm HMC; and
- specific mineral grains identified in the FSHMC can easily be revisited for more detailed analysis (e.g. laser-ablation inductively coupled plasma mass spectrometry (LA-ICP-MS)) because they are already mounted and polished.

This last point could be of importance for certain minerals that need to be characterized geochemically to be related to a porphyry copper source (cf. group 2 PCIM described in Plouffe and Ferbey, 2017). For example, the study of zircon

REE composition as related to porphyry fertility (Ballard et al., 2002; Dilles et al., 2015; Bouzari et al., 2016; Lu et al., 2016; Lee et al., 2017; Loader et al., 2017; Plouffe et al., 2019) could be applied to this mineral in the FSHMC; zircon grains large enough for LA-ICP-MS analysis were identified in our samples (Fig. 11).

In our study, the MLA-SEM results are based on the area per cent of two PCIM in 30 mm grain mounts of the FSHMC of till samples. These MLA-SEM results could be further processed to provide additional information. For example, Loughheed et al. (this volume) processed the MLA-SEM results to determine the number of mineral grains, which, combined with the area per cent, can provide valuable information about the dominant form of a mineral and,

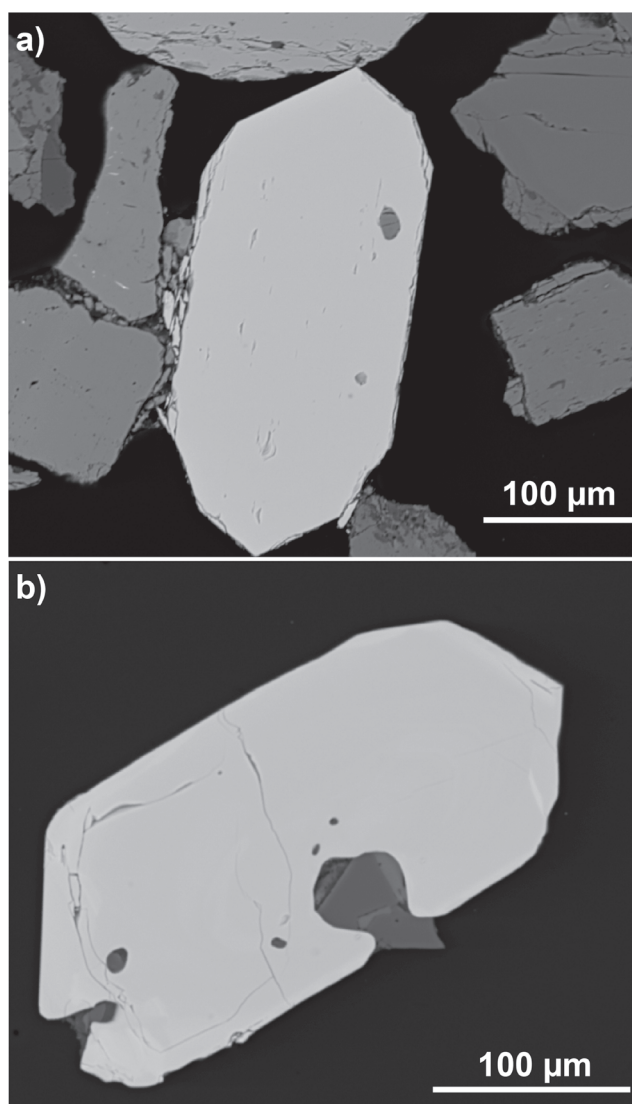


Figure 11. Backscattered-electron images of zircon from the fine-sand, heavy-mineral concentrate of till samples from porphyry copper study sites in British Columbia: **a)** sample 11PMA033A01 from Gibraltar and **b)** sample 15PMA005A01 from Highland Valley Copper.

potentially, the anomalous nature of a sample. Large grain counts combined with small area per cent values likely reflect the dominant presence of inclusions or small mineral particles on polymineral grains; conversely, small grain counts combined with large area per cent values suggest the presence of discrete mineral particles. For example, in the 0.185 to 0.250 mm HMC fraction of one till sample at the Izok Lake volcanogenic massive-sulfide deposit, galena abundance reported as area per cent is low and non-anomalous; however, the large number of small galena particles in this same sample makes it anomalous (Lougheed et al., this volume).

CONCLUSION

Using mineralogy determined by MLA-SEM of the FSHMC of 91 till samples from four porphyry copper study sites, we show that chalcopyrite is more abundant in till near mineralization at three out of four sites and that epidote, dominantly derived from hydrothermal alteration zones, is more abundant near porphyry mineralization at the four sites. These results corroborate previous mineralogical investigations of the MSHMC determined by optical methods, demonstrating that till mineralogy is an effective method to detect porphyry copper mineralization and associated alteration zones that were exposed to glacial erosion. The spatial distribution of these minerals in till follows the patterns of established ice-flow movements. In mineral exploration, till mineralogical anomalies could be traced to their potential bedrock source using reconstructed ice-flow vectors. Smaller (5–8 kg) bulk-till samples are required to obtain a sufficient FSHMC for MLA-SEM, which is an advantage over the 9 to 15 kg samples typically required to process the MSHMC for PCIMs. A reconnaissance till-sampling program aimed at determining the potential of porphyry copper mineralization in greenfield regions would benefit from smaller samples treated for MLA-SEM and geochemical analysis. Detailed follow-up could be pursued in targeted anomalous areas with a combination of PCIMs identified in the FSHMC and the MSHMC. Future research should test the identification of PCIMs by MLA-SEM in stream sediments of glaciated and unglaciated areas.

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APPENDIX A

Results of mineral liberation analysis by scanning electron microscopy (MLA-SEM) of the heavy fine sand fraction of till

This file [POR-11_Plouffe et al_Appendix A.xlsx](#) contains the heavy mineralogy of the fine sand fraction (>3.2 SG; 0.125–0.180 mm) as determined by MLA-SEM and the chalcopyrite and epidote content of the heavy medium sand fraction (>3.2 SG; 0.25–0.50 mm) of till as determined by optical mineralogy (Ferbey et al., 2016; Plouffe and Ferbey, 2016). The file includes sample locations and a short legend. This Appendix has not been edited to Geological Survey of Canada specifications.