Detecting porphyry Cu-Mo mineralization using major oxides and pathfinder elements in subglacial till, Highland Valley mine area, south-central British Columbia



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Recommended citation: Shewchuk, C., Ferbey, T., and Lian, O.B., 2020. Detecting porphyry Cu-Mo mineralization using major oxides and pathfinder elements in subglacial till, Highland Valley mine area, south-central British Columbia. In: Geological Fieldwork 2019, British Columbia Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey Paper 2020-01, pp. 169-187.

Abstract

Major oxides and pathfinder elements are not typical analytes used in drift prospecting. Testing these analytes by applying principal component analysis to published data from the silt-plus-clay (<0.063 mm) fraction of subglacial tills near the Highland Valley mine, we find that the major oxides Al₂O₃ Fe₂O₃, K₂O, and Na₂O can detect drift-covered porphyry alteration and Cu-Mo mineralization. In addition, the pathfinder elements Pb, Zn, As, and Sb can also identify local dispersal from drift-covered porphyry Cu-Mo (and related) mineralization, and CaO and Ni are linked to peripheral mafic phases of the Guichon Creek batholith (Late Triassic) and regional-scale basalt flows of the Kamloops Group (Eocene). However, Ag, Hg, and Mn values in till do not reliably detect porphyry mineralization, nor do they have a coherent signal that can be related to a specific bedrock unit.

Keywords: Till geochemistry, calc-alkaline porphyry, major oxide, pathfinder element, drift prospecting, Highland Valley mine, Guichon Creek batholith

1. Introduction

Calc-alkaline Cu-Mo and alkalic Cu-Au porphyries are common mineral exploration targets in British Columbia, and many have been developed into producing mines (Fig. 1; e.g., Gibraltar, Mount Polley, New Afton, Copper Mountain, and Highland Valley). Although continuous bedrock outcrops are rare because of extensive and commonly thick (>2 m)Quaternary drift deposits, the Interior Plateau is underlain by rocks of the Quesnel and Stikine terranes, which have high potential to host buried porphyry deposits. New buried discoveries will likely rely on surface sediment geochemistry and mineralogy to see through the glacial sediment cover. Drift prospecting can be used to assess the mineral potential of glaciated terrain and is ideally suited to explore for porphyry mineralization in the Interior Plateau. The British Columbia Geological Survey (BCGS) and Geological Survey of Canada (GSC) have been developing drift prospecting in the province for decades and have built up a catalogue of case studies that demonstrate its effectiveness (Bustard and Ferbey, 2017). Most of these studies focus on commodity and pathfinder element determinations on the matrix of subglacial tills (e.g., Plouffe and Ballantyne, 1993; Levson et al., 1994; Plouffe and Williams, 1998; Levson, 2002; Ferbey, 2011). More recent work has focussed on indicator mineral grain abundances in subglacial tills (e.g., Hashmi et al., 2015; Ferbey et al., 2016; Plouffe et al., 2016).

With notable exceptions (e.g., Cook and Fletcher, 1993), the effectiveness of major element oxides at detecting dispersal from buried mineralized bedrock sources has not been examined. The present study complements previous work in the Highland Valley mine area (Ferbey et al., 2016) and uses analytical data from this work. We look for statistically significant correlations between commodity elements (Cu, Mo) and major oxides (Al₂O₃, CaO, Fe₂O₃, K₂O, Na₂O) and pathfinder elements (Ag, As, Hg, Mn, Ni, Pb, Sb, Zn) in subglacial till and assess their spatial distribution to determine if they can detect porphyry Cu-Mo mineralization at the Highland Valley mine.

2. Background

2.1. Porphyry deposits

Porphyry systems are generated mainly in magmatic arcs where metal-rich hydrothermal fluids move through, and interact with, batholith-scale bodies and adjacent country rock to form mineral deposits (Sinclair, 2007; Berger et al., 2008; Sillitoe, 2010). Undeformed porphyry deposits display concentric alteration zones where the primary dispersion of major elements is predominantly controlled by hydrothermal alteration and mineralization processes (Fig. 2; Olade, 1977; Sillitoe, 2010). Mineralogical variation in these zones, some of which is common to all porphyry systems, is generally predictable. However, mineralogical details can vary from deposit to deposit and depend on the composition of the



Fig. 1. Location of study area (modified from Ferbey et al., 2016). Terranes of the southern Canadian Cordillera after Nelson et al. (2013).

intrusion and the country rocks, the temperature and chemistry of the hydrothermal fluids, and the interaction between these fluids and ambient water (Byrne et al., 2013; Sillitoe, 2010).

2.2. Drift prospecting

Drift prospecting is a geochemical exploration method used to assess mineral potential in glaciated terrain (Fig. 3; e.g., Levson, 2001; Lian and Hickin, 2017). The elemental and mineralogical composition of a subglacial till is dependent on the material exposed at surface to glacial erosion. Minerals like apatite, epidote, jarosite, and chalcopyrite (recovered from the 0.25 mm to 0.5 mm fraction of subglacial till matrix) can be indicators of porphyry mineralization (Kelley et al., 2011, Mao et al., 2016, 2017; Plouffe and Ferbey, 2017). Determinations on the <0.063 mm size fractions for commodity elements, pathfinder elements and, potentially, major element oxides, can also be used to explore for mineralized bedrock subcrop (Levson, 2001). A detailed multi-element-mineral assemblage investigation on subglacial till matrix can potentially be used to identify the porphyry system zones that were eroded and incorporated into subglacial tills because of the mineralogical variability in each (Fig. 2; Plouffe and Ferbey, 2017).

2.3. Principal component analysis

Principal component analysis (PCA) is a multivariate statistical technique that is used to reduce multi-dimensional datasets (Gazley et al., 2015). It is ideally suited for exploring large geochemical datasets consisting of many samples



Fig. 2. Porphyry system zonation and mineralogy (modified from Sillitoe, 2010). Mineral abbreviations: ab=albite, act=actinolite, alu=alunite, au=gold, bn=bornite, bt=biotite, cb=carbonate, ccp=chalcopyrite, chl=chlorite, cv=covellite, dck=dickite, eng=enargite, ep=epidote, hem=hematite, kfs=potassium feldspar, kln=kaolinite, mag=magnetite, mo=molybdenite, prl=pyrophyllite, py=pyrite, qz=quartz, ser=sericite. Three scenarios showing different levels of erosion, where mineral contribution to subglacial till composition depends on the porphyry zone(s), if any, exposed to glacial erosion (from Plouffe and Ferbey, 2017).



Fig. 3. Drift prospecting dispersal model (modified after Miller, 1984). Deeper blue shades indicate greater element and indicator mineral values.

with determinations for many analytes (Chen et al., 2019). Principal component analysis concentrates on variance, but also considers covariance and correlations (Jolliffe, 2011) and, in the case of geochemistry, calculates which analytes best summarize the variation of the dataset (Abdi and Williams, 2010). Eigenvectors can also be included in PCA plots, with their length proportional to the analyte's influence on data set variance, and their direction indicating covariance with other analytes. Eigenvector angles of less than 90° between analytes indicate a positive correlation, an angle of 90° indicates zero correlation, and angles greater than 90° signify a negative correlation.

3. Study area

The Guichon Creek batholith (Fig. 1) hosts the porphyry Cu-Mo deposits at the Highland Valley mine (Byrne et al., 2013). Quaternary sediments generally cover bedrock. Where the cover is thick (> 2m), bedrock is exposed at the stoss ends

of crag and tails and in deeper road cuts. Where the cover is thin, bedrock is commonly exposed as discontinuous outcrop (Ferbey et al., 2016).

3.1. Regional bedrock geology

The study area is in the Quesnel terrane, which includes richly endowed Triassic and Jurassic island arc volcanosedimentary and intrusive rocks (McMillan et al., 2009; Logan and Mihalynuk, 2014). The Guichon Creek batholith (Late Triassic) is a large calc-alkaline body, 30 km wide and 70 km long (Roy and Clowes, 2000). It is zoned, with a mafic facies on its margins and a younger more felsic facies in its interior (Casselman et al., 1995; McMillan et al., 2009; Byrne et al., 2013; Lesage et al., 2019; Fig. 4). The porphyry deposits at the Highland Valley mine (Bethlehem, Valley, Lornex, Highmont, and JA) are hosted in the younger, more felsic rocks of the Bethlehem and Bethsaida phases (Fig. 4; Byrne et al., 2013).

Mineralization occurs as vein fills, disseminations in veins,



Fig. 4. Bedrock geology of the Guichon Creek batholith and Highland Valley mine area (McMillan et al., 2009; Cui et al., 2017) with subglacial till sample locations. Highland Valley mine porphyry centres are shown with hatched red and labeled.

fracture halos, breccia infills and disseminations, and along faults (Byrne et al., 2013), and includes chalcopyrite, bornite, and molybdenite (Casselman et al., 1995). The deposits contain a bornite-rich core, which transitions outwards into chalcopyrite-rich domains. Alteration minerals include quartz, potassium feldspar, sericite, biotite, anhydrite, magnetite, calcite, hematite, kaolinite, chlorite, epidote, and fluorite; propylitic alteration (sericite, chlorite, epidote) extends outwards up to 15 km from the main deposits (Casselman et al., 1995; Byrne et al., 2013; Lesage et al., 2019). At the Bethlehem, JA and Valley deposits, K₂O and K₂O/Na₂O ratios decrease away from the inner zones of intense hydrothermal alteration and mineralization, whereas concentrations of Na₂O, CaO, MgO and total Fe (as Fe_2O_3) increase (Olade, 1977).

3.2. Quaternary geology

The Highland Valley mine area was covered by the Cordilleran ice sheet during the Late Wisconsinan glaciation (Clague and Ward, 2011 Atkinson et al., 2016). Except for JA, the deposits at Highland Valley mine were at least partially exposed to glacial erosion during the Late Wisconsinan and then covered by glacial sediments (Bobrowsky et al., 1993; Byrne et al., 2013). JA is overlain by Tertiary sedimentary bedrock, which protected it from glacial erosion during the Quaternary (Lesage et al., 2019).

Glaciers advanced out of accumulation areas to the east and west of the study area at the onset of glaciation, coming together to form an ice divide north of the study area (~52° north) during the Late Wisconsinan glacial maximum (Clague and Ward, 2011; Bobrowsky et al., 1993; Ferbey et al., 2016). Based on multi-scale ice-flow indicators, regional ice flow was initially to the south-southeast, but was later to the southeast (Fig. 5; Bobrowsky et al., 1993; Ferbey et al., 2016; Plouffe and Ferbey, 2018).

4. Methods

We chose the major oxides Al_2O_3 , CaO, Fe_2O_3 , K_2O , Na_2O , and pathfinder elements Ag, As, Hg, Mn, Ni, Pb, Sb, and Zn, from the silt plus clay-size till fraction (<0.063 mm) for statistical analysis because they are in calc-alkaline porphyry systems and can be linked to the mineralogy of specific alteration zones in these systems (Olade, 1977; Panteleyev, 1995; Sillitoe, 2010). We compared the concentrations of these oxides and



Fig. 5. Ice-flow indicators of the Highland Valley mine area (after Ferbey et al., 2013).

elements to Cu and Mo, which have been demonstrated to detect porphyry Cu-Mo mineralization at Highland Valley mine (Ferbey et al., 2016). The following summarizes the geochemical datasets and the statistical and spatial analyses we used to assess if major oxides and pathfinder elements in till can detect covered bedrock mineralization.

4.1. Till geochemical data

Existing geochemical data from 95 subglacial till samples, originally reported by Ferbey et al. (2016), were used for this study. Samples were collected from 130 to 150 cm below surface at road and stream cuts largely within the confines of the Guichon Creek batholith, including exposures at the Highland Valley mine (Fig. 4). These 1 to 2 kg samples were dry sieved at the Sedimentology Laboratory of the GSC (Ottawa, ON) to produce a silt plus clay-sized pulp (<0.063 mm). All analytical procedures were conducted at Bureau Veritas Commodities Canada Ltd. (Vancouver, BC); these are detailed in Ferbey et al. (2016) and summarized here. Sample aliquots of 0.2 g were analyzed for major elements by lithium metaborate/ tetraborate fusion and inductively coupled plasma emission spectrometry (ICP-ES; laboratory code LF200). Aliquots of 30 g were analyzed for trace elements by modified aqua regia inductively coupled plasma mass spectrometry (ICP-MS; laboratory code AQ252 EXT REE). In the total fusion method the sample material is totally decomposed, whereas with aqua regia digestion some of the sample may remain, depending on the element and the mineral phase (e.g., sulphide minerals are soluble in aqua regia but silicate minerals are not). Total trace element data were not used here. Blanks, analytical duplicates and field duplicates were inserted into the sample sequence to assess precision and accuracy (Spirito et al., 2011; McClenaghan et al., 2013; Ferbey et al., 2016). Stated analytical detection limits, and the decomposition and analytical methods used for each analyte are presented in Table 1.

4.2. Statistical data analysis

Log-transformed data were used to produce a correlation matrix, which was then used to calculate principal components and generate principal component plots using R (R Core Team, 2019). Graduated symbols were used to compare the spatial distribution of element concentrations at till sample locations. The commodity elements Cu and Mo reliably identify mineralized bedrock at Highland Valley mine (Ferbey et al., 2016), differentiating this bedrock source from other potential sources in the Guichon Creek batholith. The analyte plots were compared to Cu and Mo plots to see if they follow a similar spatial trend, with higher values near porphyry sources at Highland Valley mine that decrease in the down-ice direction.

5. Results

Summary statistics for the elements and oxides we consider are presented in Table 2. Percentile class breaks (\leq 50, >50-70, >70-90, >90-95, >95) are used in proportional symbol plots to categorize data because they do not bias the classification

Table 1. Detection limits, units, and analytical methods.

Analyte	Detection limit	Unit	Analytical method
Ag	2	ppb	AR ICP-MS
As	0.1	ppm	AR ICP-MS
Cu	0.01	ppm	AR ICP-MS
Hg	5	ppb	AR ICP-MS
Mn	1	ppm	AR ICP-MS
Mo	0.01	ppm	AR ICP-MS
Ni	0.1	ppm	AR ICP-MS
Pb	0.01	ppm	AR ICP-MS
Sb	0.02	ppm	AR ICP-MS
Zn	0.1	ppm	AR ICP-MS
Al_2O_3	0.01	%	Li fusion ICP-ES
CaO	0.01	%	Li fusion ICP-ES
Fe ₂ O ₃	0.01	%	Li fusion ICP-ES
K ₂ O	0.01	%	Li fusion ICP-ES
Na ₂ O	0.01	%	Li fusion ICP-ES

Table 2. Summary statistics for silt plus clay-sized fraction (<0.063 mm) of till samples (n=95).

Analyte	AR ICP-MS	Minimum	Mean	Median	95 th percentile	Maximum
Ag (ppb)	AR ICP-MS	4	59	39	115	559
As (ppm)	AR ICP-MS	1.2	4.4	3.7	8.6	39.4
Cu (ppm)	AR ICP-MS	37.04	243.50	178.13	611.42	1706.97
Hg (ppb)	AR ICP-MS	2.5	40.7	32.0	100	211.0
Mn (ppm)	AR ICP-MS	227	529	527	766	1251
Mo (ppm)	AR ICP-MS	0.48	2.23	1.13	8.14	28.87
Ni (ppm)	AR ICP-MS	5.1	22.2	21.1	39.3	55.6
Pb (ppm)	AR ICP-MS	1.65	5.93	3.33	7.62	216.20
Sb (ppm)	AR ICP-MS	0.11	0.35	0.30	0.59	0.98
Zn (ppm)	AR ICP-MS	18.1	50.59	49.8	78.2	122.40
Al ₂ O ₃ (%)	Li fusion ICP-ES	13.20	15.63	15.62	17.06	17.70
CaO (%)	Li fusion ICP-ES	2.51	4.95	4.72	7.36	10.71
$Fe_{2}O_{3}(\%)$	Li fusion ICP-ES	3.64	6.12	6.32	7.60	8.19
K ₂ O (%)	Li fusion ICP-ES	1.39	1.79	1.79	2.08	2.46
Na ₂ O (%)	Li fusion ICP-ES	2.70	3.60	3.55	4.29	4.92

(Levson, 2001). For the discussion that follows, background concentrations are defined as the mean for a given element; >95th percentile concentrations are considered elevated. Analytes discussed here roughly conform to a log-normal distribution.

5.1. Statistical analysis

Correlation values with respect to Cu in a log-transformed correlation matrix (Table 3) were used to assess the effectiveness of selected analytes at detecting porphyry mineralization. A higher value indicates a stronger positive or negative correlation with Cu values. Ideally, the correlation would be positive and closer to 1, although a strong negative correlation could also be meaningful. The analytes Ag, Mo, Ni, Al_2O_3 , CaO, K_2O , and Fe_2O_3 have a statistically significant correlation with Cu at $P_{0.05}$, but the analytes As, Hg, Mn, Pb, Sb, Zn, and Na₂O do not (Table 3).

The first three principal components account for 77.0% of the variability within the dataset and so were chosen for analysis. Principal component plots (PC1 versus PC2, PC1 versus PC3, and PC2 versus PC3) visually illustrate the statistical correlation between analytes and commodity elements. In all

	Ag	As	Cu	Hg	Mn	Mo	Ni	Pb	Sb	Zn	Al_2O_3	CaO	Fe ₂ O ₃	K ₂ O	Na ₂ O
Ag	1.000														
As	0.468	1.000													
Cu	0.289	0.187	1.000												
Hg	0.436	0.511	-0.044	1.000											
Mn	0.412	0.503	-0.038	0.426	1.000										
Mo	0.494	0.472	0.736	0.134	0.167	1.000									
Ni	0.267	0.331	-0.373	0.437	0.588	-0.172	1.000								
Pb	0.156	0.406	0.052	0.208	0.496	0.162	0.243	1.000							
Sb	0.314	0.714	0.125	0.525	0.453	0.311	0.113	0.456	1.000						
Zn	0.419	0.654	0.162	0.364	0.770	0.302	0.499	0.735	0.573	1.000					
Al ₂ O ₃	0.041	0.022	0.526	-0.201	0.058	0.592	-0.278	0.306	-0.006	0.283	1.000				
CaO	0.271	0.117	-0.455	0.349	0.271	-0.388	0.526	-0.135	0.084	0.067	-0.739	1.000			
Fe ₂ O ₃	0.148	0.326	-0.368	0.404	0.353	-0.328	0.792	0.143	0.158	0.300	-0.459	0.535	1.000		
K ₂ O	0.226	0.062	0.328	0.125	0.111	0.225	0.112	0.189	-0.147	0.235	0.260	-0.193	0.027	1.000	
Na,O	-0.327	0462	0.128	-0.568	-0.656	0.105	-0.726	-0.283	-0.306	-0.544	0.315	-0.484	-0.759	-0.239	1.000

Table 3. Pearson correlation matrix of log-transformed data. Bold type values are statistically significant correlations with Cu at $P_{0.05}$ (n=95).

three plots, Mo, Al_2O_3 , and K_2O are positively correlated to Cu (Figs. 6-8) and Ni, Fe_2O_3 , and CaO are negatively correlated (Figs. 6-8). This element assemblage (minus Ni) might be expected from a calc-alkaline porphyry Cu-Mo system when element signatures from the mineralized core and peripheral hydrothermal alteration are accounted for (Panteleyev et al., 1995). These relationships with Cu are stronger than those of As, Ag, Hg, Sb, Zn, and Na₂O, which are only positively correlated in two plots, PC1 versus PC2 (Fig. 6) and PC1 versus PC3 (Fig. 7). Mn and Pb have a variable and weak correlation with Cu (Figs. 6-8). These relationships support the correlation values to Cu presented in Table 3 with one exception. It is unknown why Ag is not positively correlated to Cu in all three plots (Figs. 6-8) given its statistically significant correlation value to Cu is 0.289, higher than As is to Cu (Table 3).

5.2. Spatial analysis

Copper shows a general trend of elevated values near the Highland Valley mine that decrease to the southeast, down ice-flow direction (Fig. 9). This plot, along with the one for Mo (Fig. 10), supports the notion that porphyry mineralization can be detected using the spatial distribution of elevated commodity element values in subglacial tills. The absence of Mo in till down ice-flow direction from Bethlehem reflects the lack of molybdenite in the deposit.

Some of the major oxide and pathfinder element concentrations follow the same trend as those of Cu and Mo. For example, Al_2O_3 is elevated within 3 km of the Valley,

Lornex and Highmont porphyry deposits (Fig. 11). Locally, >90th percentile values of K₂O can occur down-ice of Valley and Highmont, but they are also in a group of samples along the eastern margin of the Guichon Creek batholith (Fig. 12). Here, Cu and Mo values range from 90th percentile (locally) down to background. Fe₂O₃, CaO, and Ni have an almost inverse spatial distribution to that of Cu and Mo (Figs. 13-15). In general, samples elevated in Fe₂O₃, CaO, and Ni are near the periphery of the Guichon Creek batholith, not near the core as with Cu and Mo. All >90th percentile values of Na₂O are in the southern part of the study area (Fig. 16), south of Lornex and Highmont, where K₂O, Fe₂O₃, CaO, and Ni are at low to background values. In this cluster, northern samples can have >90th percentile values of Cu and Mo, although most samples have <90th percentile concentrations.

The spatial agreement between elevated Pb, Zn, As, and Sb values, and Cu, is less robust (Figs. 17-20). A group of samples west, and immediately down-ice, of Valley and Lornex deposits have >90th percentile values of Pb, Zn, and As. Down-ice of Lornex is one sample with >95th percentile Sb. Some of these same samples, or neighbouring samples, can also have above background Cu and Mo values. The elements Ag, Hg, and Mn have spatial distributions that do not follow that of Cu and Mo; they are more diffuse regionally and are not shown here. They could still be related to mineralized sources hosted by the Guichon Creek batholith (indicating dispersal that is local and short), but do not have the same response as Cu and Mo to known sources of mineralization at Highland Valley mine.



Fig. 6. Principal component analysis results for PC1 and PC2.



Fig. 7. Principal component analysis results for PC1 and PC3.

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Fig. 8. Principal component analysis results for PC2 and PC3.

6. Discussion

This study shows that major oxides measured in subglacial till samples have the potential to detect porphyry mineralization and alteration associated with emplacement of the Guichon Creek batholith. This conclusion is supported by the calculated correlation matrix (Table 3), visual correlations with commodity elements shown in PCA plots (Figs. 6-8), and by the spatial distribution of elevated values relative to known sources of bedrock mineralization and hydrothermal alteration (Figs. 9-20). This study also shows that major oxide and pathfinder element concentrations can differentiate other rock types at the batholith and regional scales.

6.1. Al,O, and K,O

 Al_2O_3 and K_2O concentrations in till can detect covered mineralized porphyry systems at the Highland Valley mine. Both have a statistically significant positive correlation to Cu values, and Al_2O_3 has a similar spatial distribution to samples elevated in Cu and Mo. Elevated Al_2O_3 could be related to biotite in zones of potassic alteration and/or other mainly phyllosilicate alteration zones that are more central to a porphyry system that also contain Cu-bearing minerals (Fig. 2, e.g., chlorite-sericite, sericite, advanced argillic). K_2O concentrations are spatially coincident with higher Cu and Mo values, but not as strongly as Al_2O_3 . They are also elevated in a group of till samples along the eastern margin of the Guichon Creek batholith, where <90th percentile Cu and Mo values (down to background) can occur. The Highmont deposit is the nearest know altered source for K_2O , but potassic alteration is only weakly developed there (Byrne et al., 2013) and it is located ~10 km up-ice from these 95th percentile K₂O values. Although the Highland Valley phase granodiorites have upwards of 13% primary K-feldspar (Byrne et al., 2013), this is likely not enough to account for the >2%K₂O found in tills there. These tills may have been derived from potassically altered rocks from a porphyry system southeast of Highmont. Olade (1977) found a positive correlation between K₂O and Cu values in porphyry deposits of the Guichon Creek batholith. It is worth noting that maximum till values of Al₂O₃ (17.8%) and K₂O (2.5%) are equal to or exceed the average compositions of intrusions in the Highland valley mine area (Al₂O₃=16.7%, K₂O=2.5%; Byrne et al., 2013), and average continental crust (Al₂O₃=15.0%, K₂O=2.6%; Wedepohl, 1995). Given that the geochemical signature of till is inherently diluted relative to its bedrock source, these tills appear to have been derived from bedrock with even greater values of Al₂O₃ and K₂O.

6.2. Na,O

Rocks in the central part of the Guichon Creek batholith seem to be responsible for the Na₂O response in tills there. These elevated values could be related to high-temperature sodiccalcic alteration (representing the deepest part of a porphyry system; Fig. 2). This agrees with the idea that the Valley deposit has been deeply eroded, exposing the lowermost phases of that porphyry system (Byrne et al., 2013). Byrne et al. (2017) mapped domains of sodic-calcic alteration up to 3 km west of Lornex and upwards of 6 km southeast of Highmont. The group of samples elevated in Na₂O are in this same area and





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Fig. 15. The spatial distribution of Ni in the silt plus clay-sized fraction (<0.063 mm) of subglacial till. Lee flow direction indicated with blue arrow. Refer to Fig. 4 for bedrock geology legend.

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Fig. 19. The spatial distribution of As in the silt plus clay-sized fraction (<0.063 mm) of subglacial till. Ice flow direction indicated with blue arrow. Refer to Fig. 4 for bedrock geology legend.

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we attribute their more diffuse spatial distribution (relative to the mapped bedrock domains) to glacial transport. A magmatic source of elevated Na₂O can be ruled out because porphyry deposits at Highland Valley mine are calc-alkaline, not alkalic.

6.3. Fe₂O₃, CaO, and Ni

Elevated Fe₂O₃, CaO, and Ni concentrations in till are peripheral to the central phases of the Guichon Creek batholith. They have statistically significant negative correlations to Cu values, and have an almost inverse spatial distribution to that of samples elevated in Cu and Mo. We rule out a relationship between Fe₂O₂ and distal pyrite alteration given that pyrite is only a minor constituent of the Highland Valley porphyry deposits (Byrne et al., 2013) and that elevated Fe₂O₂ (up to 8%) is distributed at the batholith scale. Elevated Fe₂O₃ in bedrock and in till could be related to propylitic alteration, given the size and fertility of the Guichon Creek batholith and that propylitic alteration can extend 10 to 15 km out from Highland Valley mine deposits (Fig. 4; Casselman et al., 1995; Byrne et al., 2013). Olade (1977) observed a similar relationship in bedrock where Fe₂O₂ and CaO values near the Bethlehem, JA, and Valley porphyry deposits increased outwards from the central mineralized core. Tills elevated in Ni and CaO values were likely derived from the more mafic intrusive phases along the batholith's periphery (e.g., Border phase, Fig. 4; Byrne et al., 2013) and/or from up-ice basalt flows of the Kamloops Group (Fig. 4, Ewing, 1981; Schiarizza and Preto, 1987). These mafic units could also be responsible for elevated Fe₂O₃ in tills, but a hydrothermal source seems more likely given that it is more widely distributed than CaO.

6.4. Pb, Zn, As, and Sb

These elements lack a statistically significant correlation with Cu values in till, but can locally have a similar spatial distribution to samples elevated in Cu and Mo. The group of samples with $>90^{th}$ percentile Pb and Zn values west of the Valley and Lornex porphyry deposits could reflect polymetallic vein mineralization. Till samples elevated in As and Sb are widely distributed (i.e., not clustered) and probably reflect dispersal from isolated bedrock sources.

6.5. Ag, Hg, and Mn

Ag, Hg, and Mn values in till do not reliably detect porphyry mineralization hosted by the Guichon Creek batholith. They are not statistically correlated to Cu values in till (except for Ag) and they have a diffuse or heterogeneous spatial distribution relative to Cu or Mo.

7. Summary and conclusions

Major oxide $(Al_2O_3, CaO, Fe_2O_3, K_2O, Na_2O)$ and pathfinder element (Ag, As, Hg, Mn, Ni, Pb, Sb, Zn) determinations on the silt plus clay sized fraction of subglacial tills were analyzed statistically and spatially to assess their ability to detect porphyry Cu-Mo mineralization at the Highland Valley mine. A correlation matrix and PCA plots were produced to statistically compare their response with that of Cu in till, which is known to reflect the presence of buried mineralized bedrock. Sample locations and concentrations were plotted to assess the spatial relationship of elevated values with locations of known sources of porphyry mineralization at the Highland Valley mine and elevated concentrations of commodity elements in till (Cu and Mo).

The major oxides Al_2O_3 , Fe_2O_3 , K_2O , and Na_2O in till can detect drift-covered porphyry alteration and Cu-Mo mineralization hosted at the Highland Valley mine. Elevated Al_2O_3 and K_2O values in till could be related to zones of potassic alteration and/or to other mainly phyllosilicate alteration zones (e.g., chlorite-sericite, sericite, advanced argillic) that are more central to a porphyry system that also contain Cu-bearing minerals. Likewise, elevated Na_2O in till could be sourced from sodic-calcic alteration, derived from the deeper, highertemperature porphyry system core at the Valley and Lornex deposits. Elevated Fe_2O_3 values in till are probably related to extensive propylitic alteration.

Pathfinder element concentrations in till can identify driftcovered porphyry Cu-Mo mineralization at the Highland Valley mine. The Valley deposit can be detected by till samples elevated in Pb, Zn, and As values, and the Lornex deposit by elevated Pb, Zn, As, and Sb values. Elevated Pb and Zn values occur in a cluster of samples west of these porphyry deposits and might record polymetallic vein mineralization.

Elevated CaO and Ni values in till could be related to different batholith phases or regional-scale bedrock units. They are likely derived from the more mafic margins of the Guichon Creek batholith (e.g., Border phase) and/or from basalt flows of the Kamloops Group exposed up ice-flow direction. Ag, Hg, and Mn values in till do not reliably detect large-scale porphyry mineralization hosted by the Guichon Creek batholith, nor do they have a coherent signal that can be related to a specific mapped bedrock unit.

Acknowledgments

We thank an anonymous reviewer for providing comments and suggestions that improved the manuscript. C. Shewchuk was supported by an Undergraduate Student Research Award from the Natural Sciences and Engineering Research Council (NSERC) of Canada and O.B Lian acknowledges support from an NSERC Discovery Grant.

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