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A. Plouffe and T. Ferbey

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2019

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

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Indicator-mineral content of bedrock and till at the Gibraltar porphyry Cu-Mo deposit and the Woodjam porphyry Cu-Au-Mo prospect, south-central British Columbia

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Abstract

The next generation of porphyry Cu deposits to be discovered in the Canadian Cordillera are likely to be found underlying glacial sediments. The recovery of minerals diagnostic of porphyry Cu mineralization, termed porphyry Cu indicator minerals (PCIM), in till and stream sediments will contribute to the discovery of buried mineralization. To identify minerals that have the potential to be used as PCIM, thirteen bedrock samples from the Gibraltar porphyry Cu-Mo deposit and ten from the Woodjam porphyry Cu-Au-Mo prospect were examined after producing mid-density (2.8-3.2 SG) and heavy (>3.2 SG) mineral concentrates. Chalcopyrite, a common Cu ore mineral, is abundant in bedrock and till in the Gibraltar and Woodjam areas making it a key PCIM. Jarosite, common in leached cap and supergene zones of porphyry Cu deposits, is generally more abundant in till near the known mineralized zones compared to surrounding regions and therefore, should be considered a PCIM diagnostic of the oxidized portion of porphyry mineralization. Other Cu (azurite, malachite, covellite, chalcocite) and Mo (molybdenite) minerals are present in mineralized bedrock but are rare or absent in till, limiting their utility as PCIM at these two study sites, but they could be important PCIM if found in detrital sediments at other sites. Other minerals (e.g. tourmaline, apatite and rutile) present in till and bedrock need to be characterized geochemically in order to be classified and used as PCIM.

Introduction

Porphyry Cu indicator minerals (PCIM) are defined here as minerals diagnostic of porphyry Cu mineralization that can be separated from and identified in surficial sediments (e.g. till, stream sediments) that have been transported away from their bedrock source (Averill, 2011; Kelley et al., 2011; Plouffe and Ferbey, 2017). Recent case studies reported PCIM in till near porphyry Cu mineralization in south central British Columbia (Ferbey and Plouffe, 2014; Hashmi et al., 2015; Plouffe and Ferbey, 2015b, 2017; Plouffe et al., 2016; Ferbey et al., 2016b) and Alaska (Kelley et al., 2011). These orientation surveys show the utility of PCIM for Porphyry Cu exploration in glaciated terrain. PCIM identified in surficial sediments are typically more abundant in till near porphyry mineralized zones compared to surrounding background regions, and can be traced to the mineralized bedrock source using glacial transport directions related to ice-flow movements. However, some minerals need to be analyzed geochemically before they can be related to a porphyry Cu source if they are not more abundant near mineralization (Plouffe and Ferbey, 2017).

In this report, we present the heavy (>3.2 specific gravity-SG) and mid-density (2.8-3.2 SG) mineralogy of bedrock samples from the Gibraltar porphyry Cu-Mo deposit and the Woodjam porphyry Cu-Mo-Au prospect of south-central British Columbia. This data set is used to identify minerals in bedrock that potentially could be recovered from till and stream sediments. We compare the heavy mineral assemblage of till and bedrock and demonstrate that not all ore minerals are PCIM as they are present in bedrock but absent or rare in till at these sites. The bedrock samples used in this study were processed for heavy mineral analysis following a procedure similar to till samples. This approach was utilized in other heavy mineral studies conducted at the Geological Survey of Canada (GSC) (e.g., Hicken et al., 2013; Normandeau and McMartin, 2013; McClenaghan et al., 2015, 2017a, b, 2019). Our heavy mineral analyses on Gibraltar samples complements the study of Kobylinski et al. (2016, 2017, 2018) on the geochemical composition of epidote, titanite, rutile, and zircon in bedrock at the same site.

Geology and mineralization

The Gibraltar Cu-Mo mine is approximately 50 km north of Williams Lake in south-central British Columbia (Fig. 1). In 2016, the deposit total reserves were estimated at 667 million tonnes and resources at 1,011 million tonnes with 0.25% Cu and 0.008% Mo (https://www.tasekomines.com/properties/gibraltar/reserves-and-resources). The deposit was discovered in about 1918 and after a long history of exploration, mining activities began in 1972 (Bysouth et al., 1995; van Straaten et al., 2013). The mine has been active since, except from 1998 to 2004 when operations were suspended due to low metal prices (Liles, 2005).

Gibraltar mine is a calc-alkaline porphyry Cu-Mo deposit hosted in the Late Triassic Granite Mountain batholith, at the western limit of the Quesnel volcanic arc terrane and in fault contact with Cache Creek terrane to the southeast (Fig. 2). As for most large intrusions of the Quesnel Terrane, the Granite Mountain batholith is polyphase including from SW to NE: i) a melanocratic quartz diorite; ii) tonalite in the central part which contains most of the mineralization (mine phase tonalite); and iii) leucocratic tonalite and trondhjemite (Drummond et al., 1973, 1976; Bysouth et al., 1995; Ash et al., 1999a, b; Ash and Riveros, 2001; Schiarizza, 2014, 2015). The western sector of the intrusion is covered by Paleogene and Neogene basalt and sedimentary rocks.

The mine includes five open-pits (Granite Lake, Pollyanna, Connector, Gibraltar East and West) centered on mineralized zones of the same name. Expansion was planned around all of these pits, towards the northwest near the Gibraltar Extension zone, and in between Gibraltar East and Pollyanna in the Connector zone (van Straaten et al., 2013) (Fig. 3). Sulphide mineralization includes chalcopyrite, molybdenite, and pyrite. Sphalerite is only present in the northwest, in Gibraltar East and West, and Gibraltar Extension. In addition to the ore deposits at Gibraltar, a number of sub-economic porphyry Cu±Mo±Au mineral occurrences are reported in the region (Fig. 2) (MINFILE, 2015).

The Woodjam Cu-Au-Mo porphyry prospect is 45 km east of the City of Williams Lake and 8 km south-southeast of Horsefly (Fig. 1). Placer and porphyry exploration has taken place in the Horsefly area since the 1800s and more detailed field work, including geological mapping, soil geochemistry, geophysics and drilling took place since the 1960s in the region of the Woodjam prospect (Sherlock et al., 2013; Sherlock and Trueman, 2013). Six mineralized zones were discovered by 2012 at Woodjam: Deerhorn, Spellbound, Megabuck, Southeast, Takom and Three Firs (Sherlock et al., 2013; Sherlock and Trueman, 2013). Mineralization is in the Takomkane batholith (Late Triassic to Early Jurassic) and associated satellite intrusions (Figs. 4 and 5). Inferred resources for Deerhorn, Southeast and Takom zones are 221.7 tonnes of ore with Cu grades varying from 0.22 to 0.31 %Cu and 0.26 to 0.49 g/t Au (Sherlock et al., 2013; Sherlock and Trueman, 2013). Copper minerals include chalcopyrite, bornite, and native Cu. Native Au is found within chalcopyrite and bornite and in alteration halos of veins at Three Firs (Vandekerkhove et al., 2014). Molybdenite is rare at Woodjam (Sherlock et al., 2013).

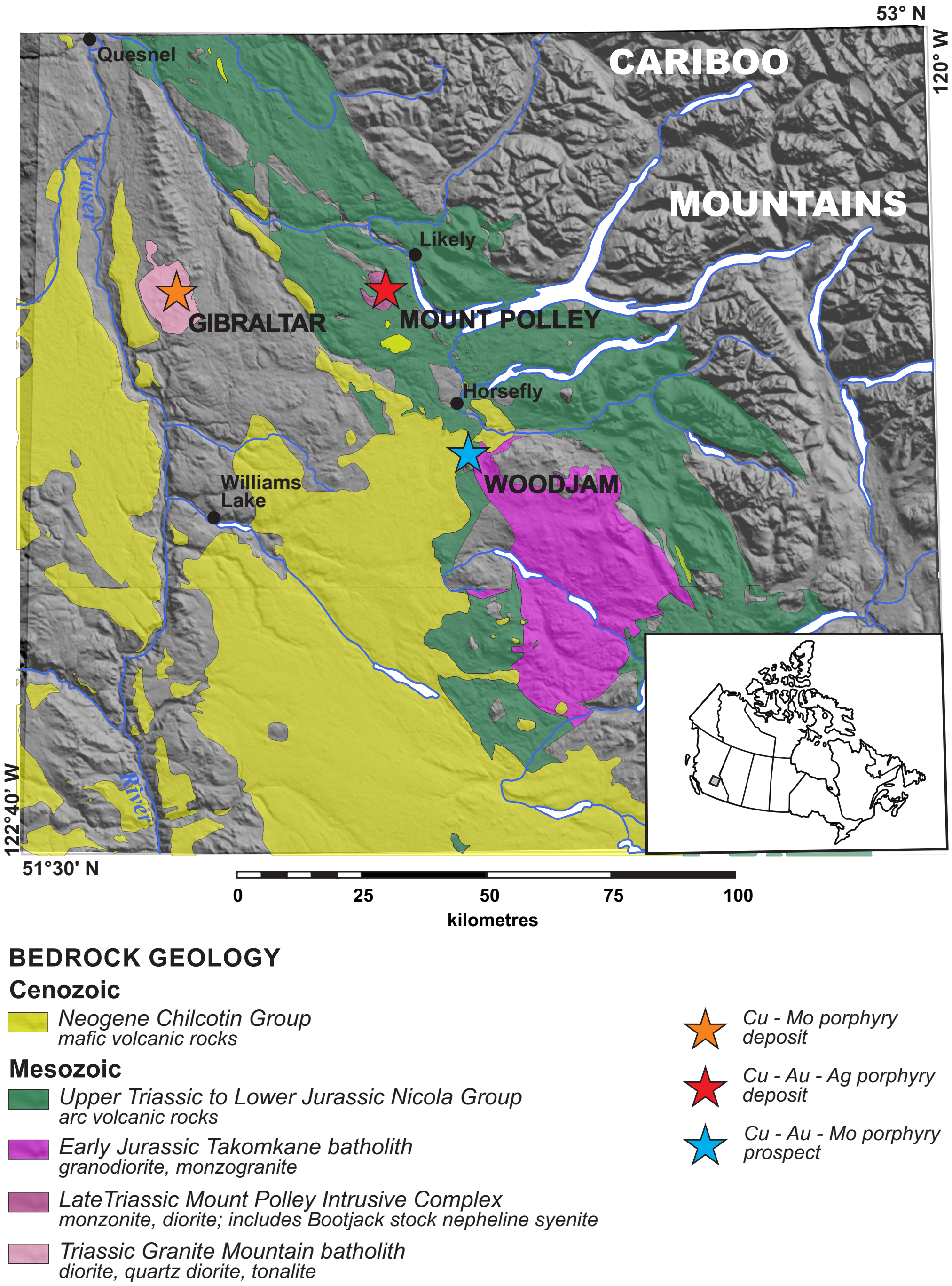

Figure 1. Location of the Gibraltar porphyry Cu-Mo deposit and Woodjam porphyry Cu-Au-Mo prospect, in south-central British Columbia. Location of Mount Polley (Cu-Au porphyry deposit) provided for reference. Bedrock geology modified from Massey et al. (2005) and Logan et al. (2010). Figure modified from Ferbey et al. (2014).

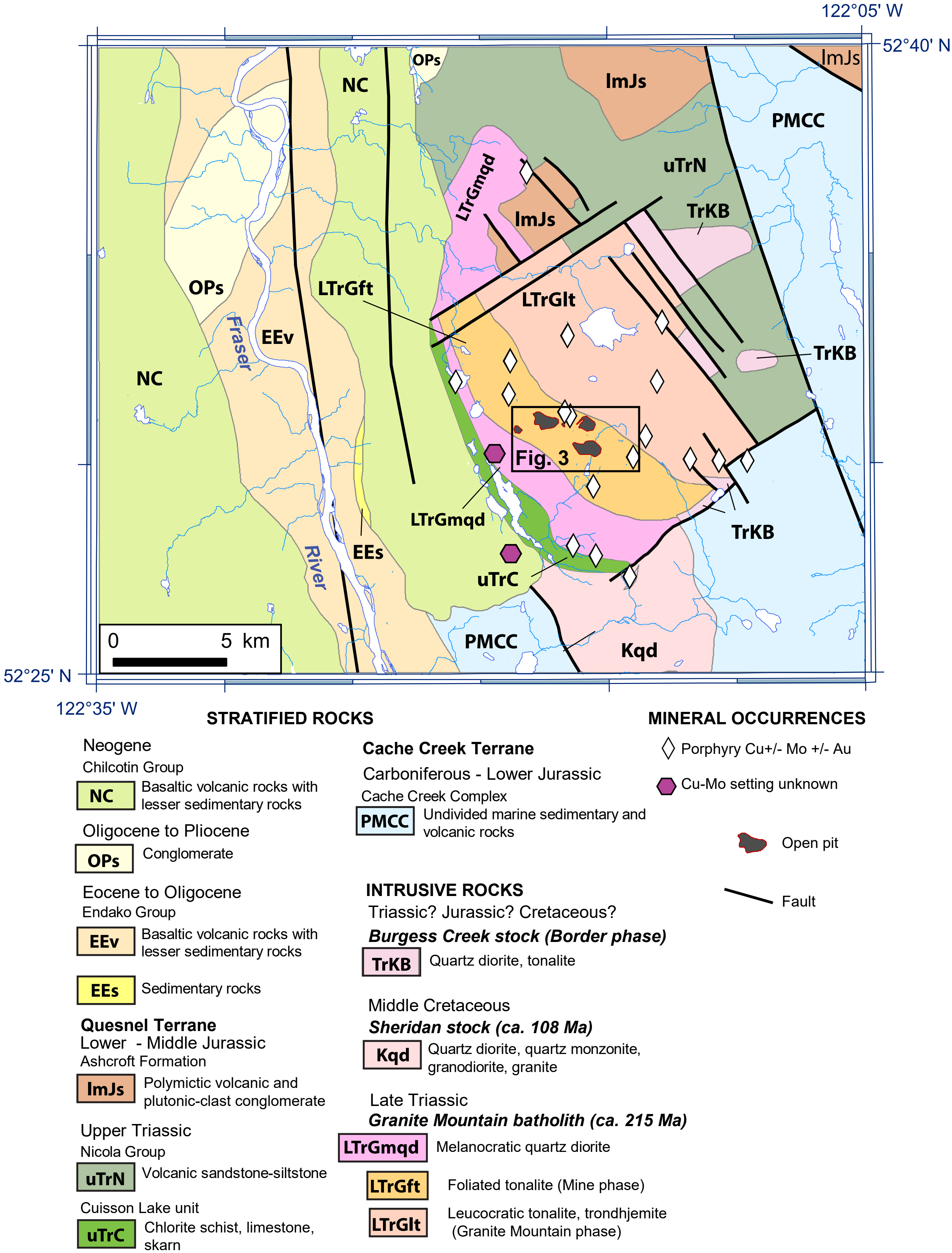

Figure 2. Bedrock geology of the Gibraltar deposit area, simplified from Ash et al. (1999b), Massey et al. (2005), and Schiarizza (2014, 2015). Mineral occurrences are from MINFILE (2015). Outline of Figure 3 is shown.

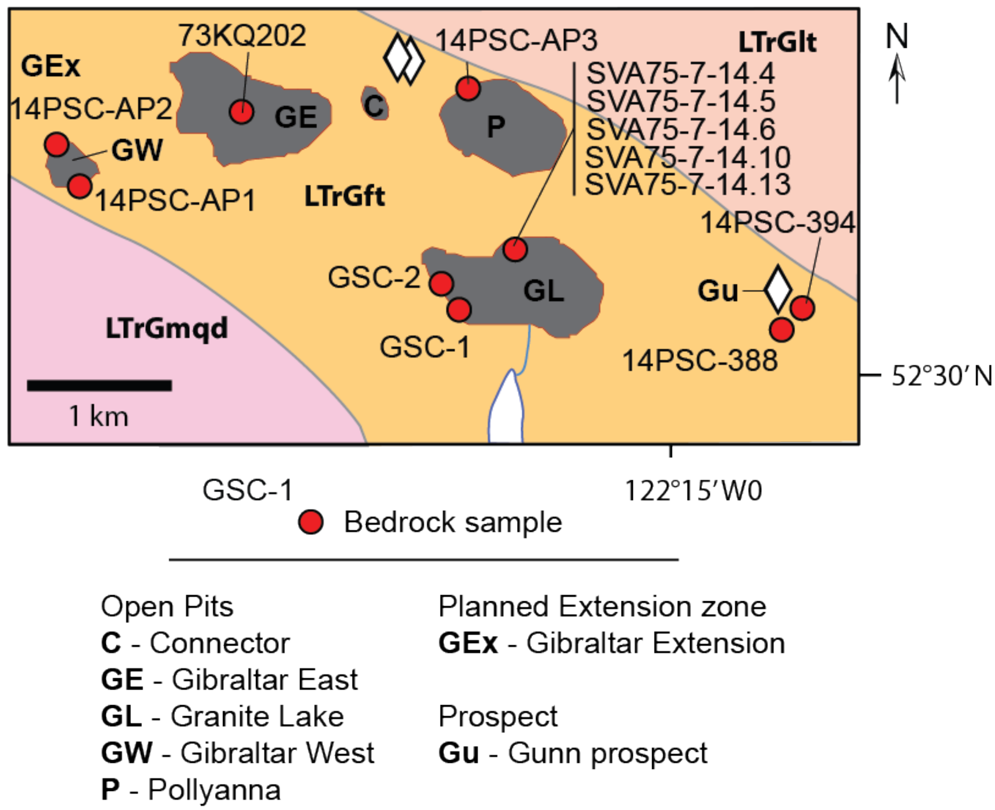

Figure 3. Location of Gibraltar bedrock samples. Pit outlines shown in dark grey with a red outline (approximate location), and planned extension modified from van Straaten et al. (2013). See Figure 2 for bedrock geology legend.

The Gibraltar and Woodjam regions were glaciated during the Late Wisconsin Fraser glaciation. Three phases of ice-flow movements (i) southeast, ii) southwest, and iii) northwest have been identified at Gibraltar, which resulted in palimpsest glacial dispersal patterns identified from till indicator minerals and geochemistry (Plouffe and Ferbey, 2015b, 2017; Plouffe et al., 2016). The Woodjam region was affected by two ice-flow movements during the last glaciation (i) southwest, and ii) northwest). Surficial geology maps were produced for the Gibraltar (Plouffe and Ferbey, 2015a) and Woodjam (Ferbey et al., 2016a) regions as part of an earlier phase of this project.

Methods

Thirteen bedrock hand samples from the Gibraltar deposit and ten previously crushed coarse (2-6 mm) bedrock core samples from the Woodjam prospect were processed for heavy mineral separation and analysis (Figs. 3 and 5). The Woodjam bedrock samples were previously crushed at a commercial geochemical laboratory employed by Gold Fields Horsefly Exploration Corporation who owned the Woodjam prospect. Bedrock samples were processed for heavy mineral separation following the same procedure employed for till samples (Plouffe and Ferbey, 2016) (Fig. 6). This procedure allows heavy mineral identification in a larger volume of rock then what is typically provided by a thin section.

Sample location information, basic descriptive notes, and drilling information are provided in Appendix 1. Seven Gibraltar samples

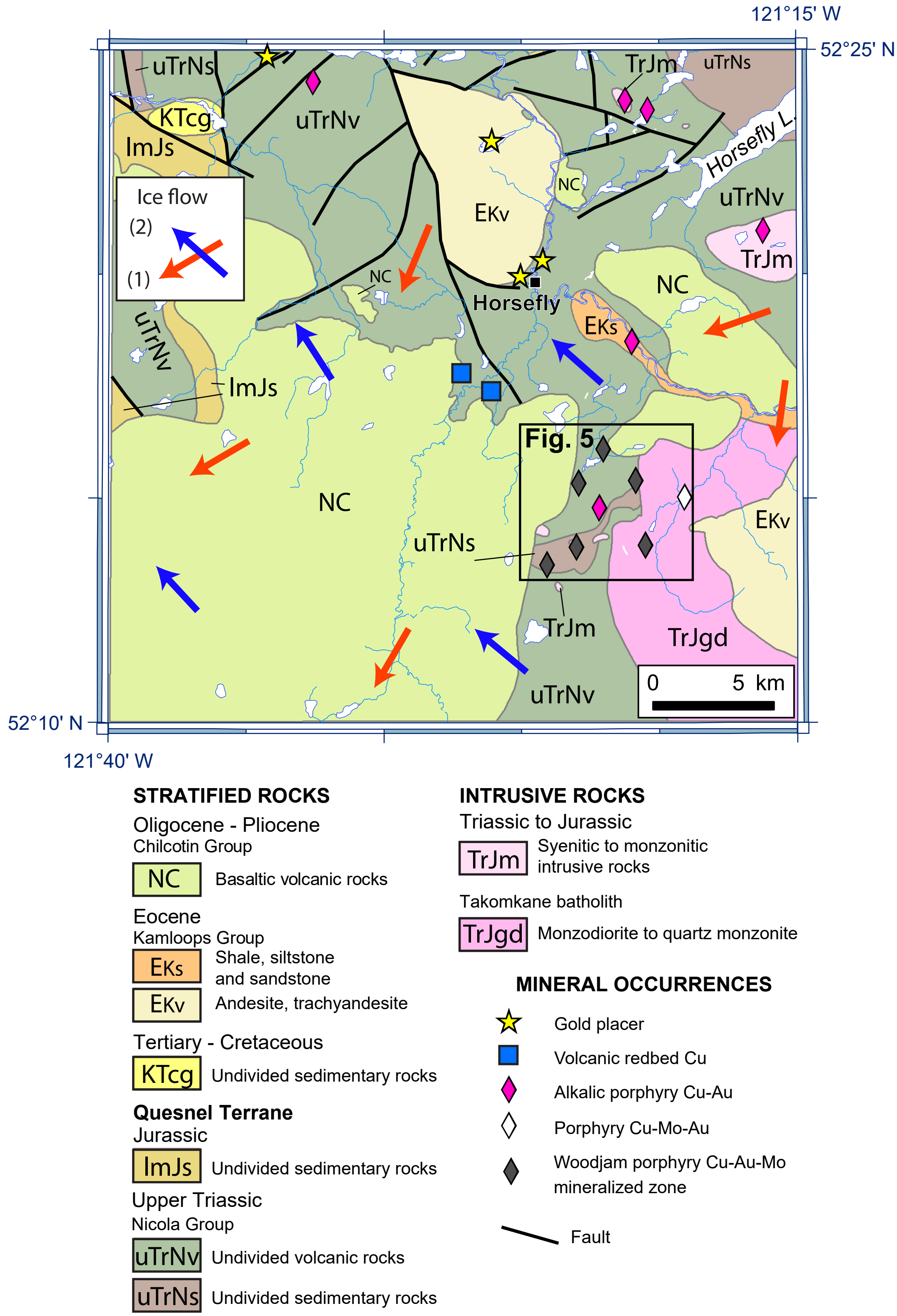

Figure 4. Bedrock geology of the Woodjam prospect, simplified from Massey et al. (2005), Logan et al. (2010), and Schiarizza (unpublished). Mineral occurrences are from MINFILE (2015).

were collected in 2014 by P. Schiarizza (British Columbia Geological Survey), L. Kennedy (University of British Columbia) and L. Goodhue (Taseko Mines Ltd.), including five samples from the mine site and two from the Gunn porphyry prospect (Minfile number 093B 003; MINFILE, 2015) located approximately 1 km east of the Granite Lake pit (Fig. 3). Six additional Gibraltar samples were recovered from the GSC archived collection. These samples were collected in 1973 and 1975 by R. Kirkham and A.E. Soregaroli in the early development stage of Gibraltar mine. All Gibraltar samples except two (14PSC-AP3 and GSC-1) contain Cu mineralization. Gibraltar hand samples were photographed before their submission for destructive heavy mineral separation and analysis (Appendix 2).

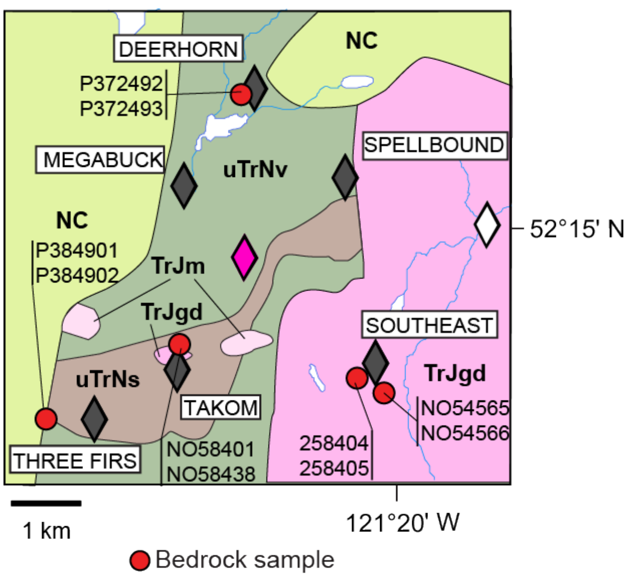

Figure 5. Location of Woodjam bedrock samples. See Figure 4 for bedrock geology legend.

At both sites, bedrock samples were collected as close as possible to the bedrock-surface sediment interface i.e., samples that reflect the shallow part of the bedrock mineralization most likely eroded by glaciers.

All samples were processed to recover heavy minerals at Overburden Drilling Management Limited (Ottawa, ON). All samples were examined with a binocular microscope and described prior to their processing (Appendix 3 BMD worksheet and Appendix 4). Hand samples (Gibraltar) and two crushed core samples (Woodjam; samples P384901 and P384902; Appendix 5B) with abundant coarse fragments were disaggregated using a CNT Spark-2 electric pulse disaggregator (EPD) until most of the material was <2 mm in diameter. Each sample was placed in a sealed plastic bag in the EPD to avoid cross contamination. Gibraltar disaggregated material and Woodjam crushed bedrock samples were then wet sieved to recover the <2 mm fraction to be used for heavy mineral separations.

The <2 mm fraction was first passed over a shaking table for a pre-concentration of the heavy fraction (Fig. 6). The table concentrate was micro-panned to produce a pan concentrate that was examined for fine gold grains, sulphides and other Cu indicator minerals (Appendices 3 and 5; Detailed VG worksheet). At this stage, mineral grains were described, measured and returned to the sample. Table concentrates were first sieved to remove the <0.18 mm fraction and then placed in heavy liquids (methylene iodide) diluted with acetone to a SG of 2.8 and 3.2 to separate a mid-density (2.8-3.2 SG) and a dense (>3.2 SG) fractions. Magnetic minerals were removed from both heavy fractions with a hand magnet. Both density fractions were sieved to 0.25-0.5 mm, 0.5-1 mm, and 1-2 mm. Weights of the processed material and of the different size and density fractions were recorded at every step (EPD Log and Processing weights worksheet in Appendix 3, and Tabling data and Processing weights worksheet in Appendix 5). The 0.25-0.5 mm and >3.2 SG fraction was passed through a Carpco® magnetic separator set at 0.6, 0.8, and 1.0 amp.

All fractions were visually examined by mineralogists with a binocular microscope. Minerals were identified based on color, luster, crystal habit, cleavage, surface texture, and paramagnetic properties. For some grains, optical

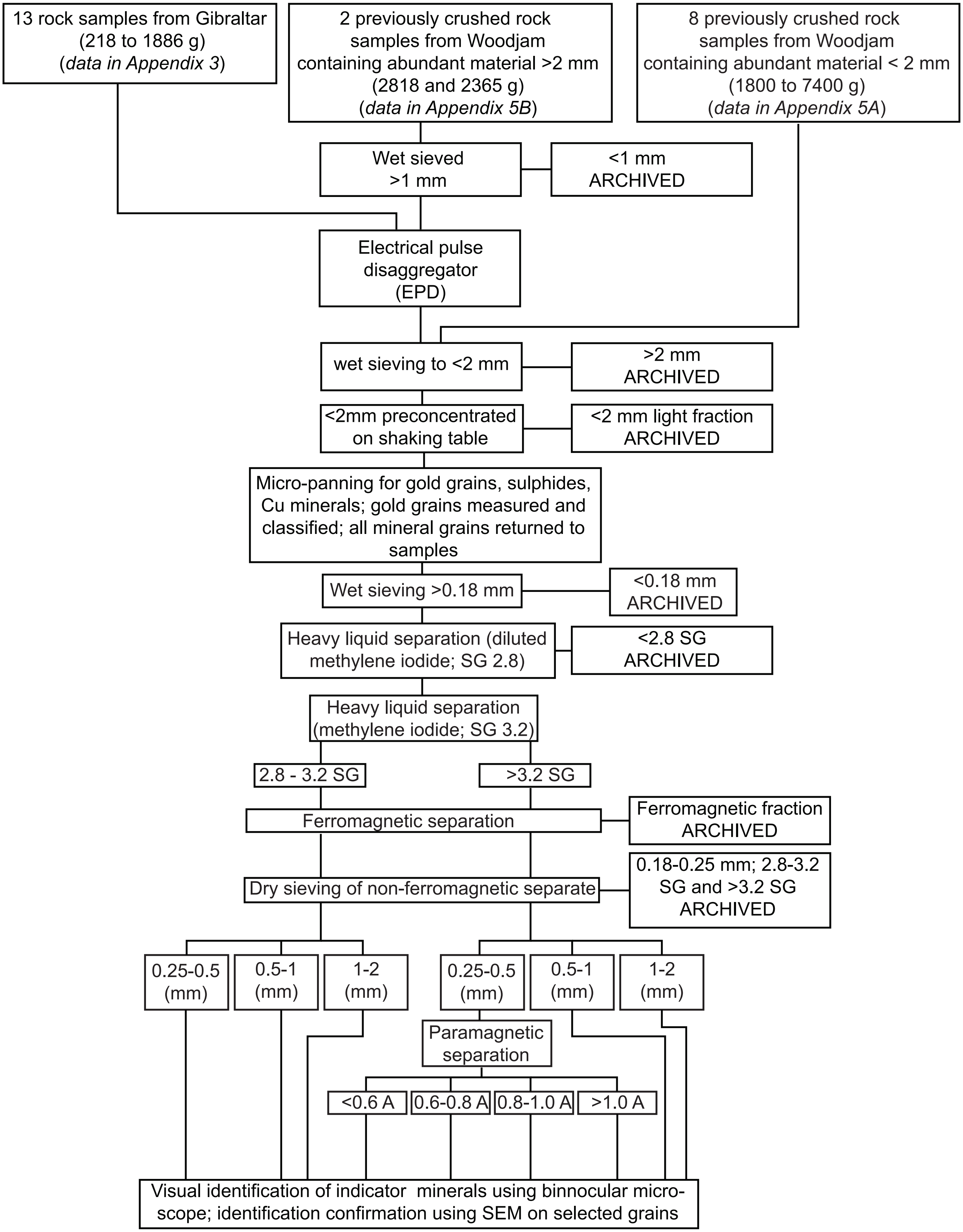

Figure 6. Flow chart for the processing of bedrock samples for heavy mineral analysis.

identification was verified with a scanning electron microscope (SEM). Mineralogical reports produced by ODM are presented in Appendix 3 for Gibraltar and Appendix 5 for Woodjam samples.

Crushed barren quartz vein samples (<2 mm, 77.7 to 96.5 g) were processed at the beginning of the sample batch and in between each Gibraltar sample to monitor cross-contamination during EPD processing. The quartz samples were disaggregated in the EPD and processed in the same way as the Gibraltar bedrock samples. The quartz samples are labelled “Blank” and their data are reported along with the data of the Gibraltar samples in Appendix 3. The vein quartz is known to naturally contain 0 to 5 pyrite grains in a 60 to 80 g sample. No quartz blanks were processed with the two Woodjam bedrock samples disaggregated with the EPD (Appendix 5B).

Results

Mineral abundances are reported as grain counts or percentages in appendices 3 and 5. Key minerals observed following micro-panning and heavy mineral separation are presented in Table 1 and 2, respectively. Heavy mineral grain counts are normalized to 1 kg using the weight of material <2 mm processed on the shaking table. Such normalization is necessary to compare mineral abundance amongst samples of variable mass.

Mineral abundances from appendices 3 and 5 are included in a spreadsheet (Appendix 6A) and shapefile (Appendix 6B), along with location information, to facilitate use in a geographic information system. Some mineral abundances are reported as percentages only with no grain counts, including results reported as trace amount: Tr. Trace amount (Tr) was converted to a numerical value of 0.1% to allow data interpretation. Metadata for the GSC Canadian Database of Geochemical Surveys (CDoGS) are provided in Appendix 7.

Quartz blanks - Out of the thirteen quartz blank samples processed, five contained no heavy minerals and eight contained between 1 to 3 grains of pyrite in the 0.050 to 0.150 mm size range of the pan concentrate (Appendix 3 ‘Detailed VG’ worksheet). As mentioned above, pyrite is known to occur naturally in the quartz vein used for this blank (0 to 5 grains per 60 to 80 g sample). The amount of pyrite detected by ODM in the quartz blanks submitted with the Gibraltar samples is below these natural concentrations. Consequently, ODM concluded that the quartz blanks contained no evidence of cross-contamination (Appendix 3 worksheet ‘Quartz cleaner’).

Unmineralized samples - Samples 14PSC-AP3 and GSC-1 are considered unmineralized because they did not contain Cu or Mo minerals. However, they contained small quantities of pyrite (0.05 to 0.125 mm in diameter) that were observed in the micro-panned concentrate. They contained no other sulphides. Three allanite grains [$(Ce,Ca,Y)_2$ $(Al,Fe,Mg)_3Si_3O_{12}(OH)$, an epidote group mineral enriched in light rare earth elements], equivalent to nine grains per 1 kg, were present in the 0.25-0.5 mm and >3.2 SG fraction of GSC-1, as confirmed by SEM analysis.

Mineralized samples - Gibraltar and Woodjam mineralized samples contained variable amounts of Cu minerals including chalcopyrite, azurite, covellite, malachite, and chalcocite observed in the mid-density and heavy mineral fractions (2.8-3.2 and >3.2 SG) and the pan concentrates (Tables 1 and 2). Only one grain of native Cu (0.050-0.150 cm) was identified in the pan concentrate of Woodjam sample P372493 (Table 1). Some minerals with a SG >3.2 were recovered in the 2.8-3.2 SG fraction (Table 2) because they were attached to light minerals (e.g. quartz, chlorite, feldspar) which decreased the total density of the grains. Molybdenite was reported in six mineralized bedrock samples and was much less abundant than the Cu minerals. Other sulphide minerals in the pan concentrates of two Woodjam samples included pyrite (present in all

Table 1. Minerals identified in the pan concentrates of bedrock samples (micro-panning)

(A) Mineral percentages (%) and grain counts (gr)

		Py (gr)	**Py (%)**	**Ccp (gr)**	**Ccp (%)**	**Bn (gr)**	**Bn (%)**	**Cct (gr)**	**Mol (gr)**	**Gn (gr)**
Formula		FeS_2		$CuFeS_2$		Cu_5FeS_4		Cu_2S	MoS_2	PbS
Specific gravity		5		4.1-4.3		5.06-5.08		5.5-5.8	4.6-4.7	7.58
Sample	**Processed weight (g)**									
GIBRALTAR unmineralized										
14PSC-AP3	520.8	30								
GSC-1	495.8	2								
GIBRALTAR mineralized										
14PSC-AP1	450.0	1,000								
14PSC-AP2	959.9	1,000								
GSC-2	846.0	5,000	0.1					50 (2)		
73KQ202	437.8	20,000	1	10						
SVA75-7-14.4	187.3	150,000	20							
SVA75-7-14.5	145.4	200,000	20	50					10	
SVA75-7-14.6	129.7			5000	0.5				20	
SVA75-7-14.10	183.7	1,000		300,000	25				20	
SVA75-7-14.13	183.8	5,000	0.5	100,000	10				2	
GUNN										
14PSC-388	935.0	1,000		500						
14PSC-394	924.2	2,000		100,000	5					
WOODJAM										
258404	1,700	1,000		n.d.	20	n.d.	1			
258405	3,000	n.d.	5	n.d.	20	n.d.	0.5		2	
NO54565	1,700	n.d.	80	200						
NO54566	3,200	n.d.	80	1,000 (4)						20
P372492	5,700	n.d.	90							
P372493	5,900	n.d.	70					2000 (4)	10	
NO58438	3,400	n.d.	40	n.d.	20	500				
NO58401	3,300	n.d.	40	n.d.	20	200				
P384901*	1,147	200								
P384902	703	n.d.	5							

Note: values in parentheses are number of grains verified with the SEM.

n.d. - mineral present in % but no grain count data to quantify

*-Undersized heavy mineral concentrate (only 0.36 g of >2.8 SG, 0.25-0.5 mm)

Py-pyrite; Ccp-chalcopyrite; Bn-bornite; Cct-chalcocite; Mol-molybdenite; Gn-galena (after Whitney and Evans, 2010)

Table 1. Cont'd. Minerals identified in the pan concentrate of bedrock samples (micro-panning)
(A) Mineral percentages (%) and grain counts (gr)

	Po (gr)	**Az (gr)**	**Mlc (gr)**	**Sch (gr)**	**nat Cu (gr)**	**nat Au (gr)**
Formula	$Fe_{1-x}S$	$Cu_3(CO_3)_2(OH)_2$	$Cu(CO_3)(OH)_2$	$CaWO_4$	Cu	Au
Specific gravity	4.58-4.65	3.8	3.6-4	6.12	8.95	19.3
Sample						
GIBRALTAR unmineralized						
14PSC-AP3						
GSC-1						
GIBRALTAR mineralized						
14PSC-AP1		2	100			
14PSC-AP2			200 (4)			
GSC-2		10 (2)				
73KQ202						
SVA75-7-14.4						
SVA75-7-14.5						
SVA75-7-14.6						
SVA75-7-14.10						1
SVA75-7-14.13						
GUNN						
14PSC-388			1000			
14PSC-394						
WOODJAM						
258404						61
258405						118
NO54565				200 (4)		
NO54566						
P372492						5
P372493					1	41
NO58438	200 (4)					201
NO58401						322
P384901*						
P384902						8

Note: values in parentheses are number of grains verified with the SEM.
n.d. - mineral present in % but no grain count data to quantify
*-Undersized heavy mineral concentrate (only 0.36 g of >2.8 SG, 0.25-0.5 mm)
Po-pyrrhotite; Az-azurite; Mlc-malachite; Sch-sheelite; nat Cu-native copper; nat Au-native gold
(after Whitney and Evans, 2010)

Table 1. Minerals identified in the pan concentrate of bedrock samples (micro-panning)
(B) Grain counts (gr) normalized to 1 kg

		Py (gr/1 kg)	Ccp (gr/1 kg)	Bn (gr/1kg)	Cct (gr/1 kg)	Mol (gr/1kg)	Gn (gr/1kg)
Formula		FeS_2	$CuFeS_2$	Cu_5FeS_4	Cu_2S	MoS_2	PbS
Specific gravity		5	4.1-4.3	5.06-5.08	5.5-5.8	4.6-4.7	7.58
Sample	**Processed weight (g)**						
GIBRALTAR unmineralized							
14PSC-AP3	520.8	58					
GSC-1	495.8	4					
GIBRALTAR mineralized							
14PSC-AP1	450.0	2,222					
14PSC-AP2	959.9	1,042					
GSC-2	846.0	5,910			59		
73KQ202	437.8	45,683	23				
SVA75-7-14.4	187.3	800,854					
SVA75-7-14.5	145.4	1,375,516	344			69	
SVA75-7-14.6	129.7		38,551			77	
SVA75-7-14.10	183.7	5,444	1,633,097			109	
SVA75-7-14.13	183.8	27,203	544,070			11	
GUNN							
14PSC-388	935.0	1,070	535				
14PSC-394	924.2	2,164	108202				
WOODJAM							
258404	1,700	588	n.d.	n.d.			
258405	3,000	n.d.	n.d.	n.d.		1	
NO54565	1,700	n.d.	118				
NO54566	3,200	n.d.	313				6
P372492	5,700	n.d.					
P372493	5,900	n.d.				2	
NO58438	3,400	n.d.	n.d.	147			
NO58401	3,300	n.d.	n.d.	61			
P384901*	1,147	174					
P384902	703	n.d.					

Note: only the grain counts are normalized to 1 kg.
n.d. - mineral present in % but no grain count data to quantify
*-Undersized heavy mineral concentrate (only 0.36 g of >2.8 SG, 0.25-0.5 mm)
Py-pyrite; Ccp-chalcopyrite; Bn-bornite; Cct-chalcocite; Mol-molybdenite; Gn-galena (after Whitney and Evans, 2010)

Table 1. Cont'd. Minerals identified in the pan concentrate of bedrock samples (micro-panning)
(B) Grain counts (gr) normalized to 1 kg

	Po (gr/1 kg)	**Az (gr/1 kg)**	**Mlc (gr/1 kg)**	**Sch (gr/1 kg)**	**nat Cu (gr/1 kg)**	**nat Au (gr/1 kg)**
Formula	$Fe_{1-x}S$	$Cu_3(CO_3)_2(OH)_2$	$Cu(CO_3)(OH)_2$	$CaWO_4$	Cu	Au
Specific gravity	4.58-4.65	3.8	3.6-4	6.12	8.95	19.3
Sample						
GIBRALTAR unmineralized						
14PSC-AP3						
GSC-1						
GIBRALTAR mineralized						
14PSC-AP1		4	222			
14PSC-AP2			208			
GSC-2		12				
73KQ202						
SVA75-7-14.4						
SVA75-7-14.5						
SVA75-7-14.6						
SVA75-7-14.10						5
SVA75-7-14.13						
GUNN						
14PSC-388			1070			
14PSC-394						
WOODJAM						
258404						36
258405						39
NO54565				118		
NO54566						
P372492						1
P372493					1	7
NO58438	59					59
NO58401						98
P384901*						
P384902						11

Note: values in parentheses are number of grains verified with the SEM.
n.d. - mineral present in % but no grain count data to quantify
*-Undersized heavy mineral concentrate (only 0.36 g of >2.8 SG, 0.25-0.5 mm)
Po-pyrrhotite; Az-azurite; Mlc-malachite; Sch-sheelite; nat Cu-native copper; nat Au-native gold
(after Whitney and Evans, 2010)

Table 2. Minerals identified in the 0.25-0.5 mm, 2.8 – 3.2 SG and > 3.2 SG fraction of bedrock samples: summary (number of grains).
(A) Reported mineral grain counts

		SG >3.2; 0.25 - 0.5 mm						
		Py (gr)	**Ccp (gr)**	**Cv (gr)**	**Cct (gr)**	**Mol (gr)**	**Az (gr)**	**Mlc (gr)**
Formula		FeS_2	$CuFeS_2$	CuS	Cu_2S	MoS_2	$Cu_3(CO_3)_2(OH)_2$	$Cu(CO_3)(OH)_2$
Specific gravity		5	4.1-4.3	4.6-4.8	5.5-5.8	4.6-4.7	3.8	3.6-4
Sample	**Processed weight (g)**							
GIBRALTAR unmineralized								
14PSC-AP3	520.8							
GSC-1	495.8							
GIBRALTAR mineralized								
14PSC-AP1	450.0	120	2					120
14PSC-AP2	959.9	40	2					200
GSC-2	846.0	800	30	7			23	2
73KQ202	437.8	5,000	150					
SVA75-7-14.4	187.3	30,000	6					
SVA75-7-14.5	145.4	40,000	19			25		
SVA75-7-14.6	129.7	3	1,000			3		
SVA75-7-14.10	183.7		70,000			50		
SVA75-7-14.13	183.8	1,500	20,000			2		
GUNN								
14PSC-388	935.0	40	80					600
14PSC-394	924.2	30	30,000			1		1
WOODJAM								
258404	1,700	15	10,000					
258405	3,000	20	15,000			8		
NO54565	1,700	20,000	1,000					
NO54566	3,200	16,000	400					
P372492	5,700	90,000	7,000					
P372493	5,900	30,000	2,500					
NO58438	3,400	15,000	5,000					
NO58401	3,300	4,000	20,000					
P384901*	1,147	20						
P384902	703	15,000	40		2			

*-Undersized heavy mineral concentrate (only 0.36 g of >2.8 SG, 0.25-0.5 mm)

Py-pyrite; Ccp-chalcopyrite; Cv-Covellite; Cct-chalcocite; Mol-molybdenite; Az-azurite; Mlc-malachite (after Whitney and Evans, 2010)

Table 2. Cont'd. Minerals identified in the 0.25-0.5 mm, 2.8 – 3.2 SG and > 3.2 SG fraction of bedrock samples: summary (number of grains).

(A) Reported mineral grain counts

	SG 2.8 - 3.2; 0.25 - 0.5 mm			
	Ccp (gr)	**Cct (gr)**	**Mol (gr)**	**Mlc (gr)**
Formula	$CuFeS_2$	Cu_2S	MoS_2	$Cu(CO_3)(OH)_2$
Specific gravity	4.1-4.3	5.5-5.8	4.6-4.7	3.6-4
Sample				
GIBRALTAR unmineralized				
14PSC-AP3				
GSC-1				
GIBRALTAR mineralized				
14PSC-AP1				50
14PSC-AP2				400
GSC-2	200			
73KQ202				
SVA75-7-14.4				
SVA75-7-14.5		150	6,000	
SVA75-7-14.6				6,000
SVA75-7-14.10		20,000		
SVA75-7-14.13		10,000		
GUNN				
14PSC-388				150
14PSC-394				
WOODJAM				
258404	5,000			
258405	4,000			
NO54565	900			
NO54566	1,500			
P372492	4,000			
P372493	5,000			
NO58438	6,000			
NO58401	6,000			
P384901*				
P384902				

*-Undersized heavy mineral concentrate (only 0.36 g of >2.8 SG, 0.25-0.5 mm)

Ccp-chalcopyrite; Cct-chalcocite; Mol-molybdenite; Mlc-malachite (after Whitney and Evans, 2010)

Table 2. Minerals identified in the 0.25-0.5 mm, 2.8 – 3.2 SG and > 3.2 SG fraction of bedrock samples: summary (number of grains).
(B) Mineral counts normalized to 1 kg

		SG >3.2; 0.25 - 0.5 mm						
		Py (gr/1 kg)	**Ccp (gr/1 kg)**	**Cv (gr/1 kg)**	**Cct (gr/1 kg)**	**Mol (gr/1 kg)**	**Az (gr/1 kg)**	**Mlc (gr/1 kg)**
Formula		FeS_2	$CuFeS_2$	CuS	Cu_2S	MoS_2	$Cu_3(CO_3)_2(OH)_2$	$Cu(CO_3)(OH)_2$
Specific gravity		5	4.1-4.3	4.6-4.8	5.5-5.8	4.6-4.7	3.8	3.6-4
Sample	**Processed weight (g)**							
GIBRALTAR unmineralized								
14PSC-AP3	520.8							
GSC-1	495.8							
GIBRALTAR mineralized								
14PSC-AP1	450.0	267	4					267
14PSC-AP2	959.9	42	2					208
GSC-2	846.0	946	35	8			27	2
73KQ202	437.8	11,421	343					
SVA75-7-14.4	187.3	160,171	32					
SVA75-7-14.5	145.4	275,103	131			172		
SVA75-7-14.6	129.7	23	7,710			23		
SVA75-7-14.10	183.7		381,056			272		
SVA75-7-14.13	183.8	8,161	108,814			11		
GUNN								
14PSC-388	935.0	43	86					642
14PSC-394	924.2	32	32,461			1		1
WOODJAM								
258404	1700	9	5,882					
258405	3000	7	5,000			3		
NO54565	1700	11,765	588					
NO54566	3200	5,000	125					
P372492	5700	15,789	1,228					
P372493	5900	5,085	424					
NO58438	3400	4,412	1,471					
NO58401	3300	1,212	6,061					
P384901*	1147	17						
P384902	703	21,337	57		3			

*-Undersized heavy mineral concentrate (only 0.36 g of >2.8 SG, 0.25-0.5 mm)

Py-pyrite; Ccp-chalcopyrite; Cv-Covellite; Cct-chalcocite; Mol-molybdenite; Az-azurite; Mlc-malachite (after Whitney and Evans, 2010)

Table 2. Cont'd. Minerals identified in the 0.25-0.5 mm, 2.8 – 3.2 SG and > 3.2 SG fraction of bedrock samples: summary (number of grains).
(B) Mineral counts normalized to 1 kg

	SG 2.8 - 3.2; 0.25 - 0.5 mm			
	Ccp (gr/1 kg)	**Cct (gr/1 kg)**	**Mol (gr/1 kg)**	**Mlc (gr/1 kg)**
Formula	$CuFeS_2$	Cu_2S	MoS_2	$Cu(CO_3)(OH)_2$
Specific gravity	4.1-4.3	5.5-5.8	4.6-4.7	3.6-4
Sample				
GIBRALTAR unmineralized				
14PSC-AP3				
GSC-1				
GIBRALTAR mineralized				
14PSC-AP1				111
14PSC-AP2				417
GSC-2	236			
73KQ202				
SVA75-7-14.4				
SVA75-7-14.5		1,032	41,265	
SVA75-7-14.6				46,261
SVA75-7-14.10		108,873		
SVA75-7-14.13		54,407		
GUNN				
14PSC-388				160
14PSC-394				
WOODJAM				
258404	2,941			
258405	1,333			
NO54565	529			
NO54566	469			
P372492	702			
P372493	847			
NO58438	1,765			
NO58401	1,818			
P384901*				
P384902				

*-Undersized heavy mineral concentrate (only 0.36 g of >2.8 SG, 0.25-0.5 mm)
Ccp-chalcopyrite; Cct-chalcocite; Mol-molybdenite; Mlc-malachite (after Whitney and Evans, 2010)

samples), galena (0.05-0.100 mm) and pyrrhotite (0.025-0.05 mm) (Table 1). Scheelite (0.025-1 mm) was present in the pan concentrate of only one Woodjam sample (NO54565; Table 1). Five grains of allanite were recovered from Gibraltar sample 14PSC-AP1 (equivalent to 11 grains per 1 kg). Gold grains were recovered from six out of eight Woodjam samples varying in abundance from 1 to 98 grains per 1 kg (Table 1). One gold grain (equivalent to 5 grains per 1 kg) was recovered in a single Gibraltar sample (SVA75-7-14.10).

Most Gibraltar samples contained small amounts of magnetic minerals (≤0.02 g equivalent to <0.01% of the >2.8 SG fraction) as reported as 'Mag HMC' in Appendix 3 worksheet 'Processing Weights'. The exception was sample SVA75-7-14.13 which contained 42.5 g of magnetic minerals (60% of the >2.8 SG fraction). Woodjam bedrock samples generally contained more magnetic minerals than Gibraltar samples but the amounts are variable (0.1 to 78.5 g equivalent to <0.01 and up to 68% of the >2.8 SG fraction) likely attesting to the heterogeneous distribution of magnetic minerals in the intrusive rocks.

Sample description – In the Gibraltar bedrock description section (Appendix 3 worksheet BMD), sample 73-KQ-202 is described as veined basalt. Given the geological setting of the sample, its description as a "foliated schistose quartz diorite", as provided by the sampler (R. Kirkham), is considered to be more accurate.

Discussion

Chalcopyrite, the predominant Cu sulphide at Gibraltar and Woodjam, was present in all mineralized bedrock samples tested. Chalcopyrite is also present in till forming a palimpsest dispersal train at Gibraltar and a regional anomaly at Woodjam, sourced from the main mineralized zones (Plouffe et al., 2016; Plouffe and Ferbey, 2017) (Fig. 7). Consequently, chalcopyrite can be considered a key PCIM in till in the Gibraltar and Woodjam areas where Cu mineralization was exposed to glacial erosion.

Although less abundant than chalcopyrite, malachite was in five bedrock samples at Gibraltar including the samples from the Gunn prospect (Table 2). In the same area, malachite is rare in till; 1 or 4 grains/10 kg in a few samples (Fig. 8). At Woodjam, malachite is not in till or in our tested bedrock samples but has been reported to be in the deposit by Sherlock et al. (2013) and Sherlock and Trueman (2013). Where malachite is recovered in till, it is a useful indicator of Cu mineralization. Its low abundance in till could reflect its low abundance in bedrock eroded by glaciers.

Three Cu minerals, azurite, chalcocite and covellite, were in a few of the Gibraltar and Woodjam bedrock samples and were reported in both deposits by others (Bysouth et al., 1995; Sherlock et al., 2013; Sherlock and Trueman, 2013; van Straaten et al., 2013). One bedrock sample from Woodjam contained a single grain of native Cu (Tables 1 and 2). Molybdenite, the key Mo ore mineral at Gibraltar and Woodjam, was observed in six bedrock samples. None of these minerals were detected in till overlying or down-ice of the deposits (Plouffe and Ferbey, 2016) which limits their use as indicator minerals at both study sites. The presence of molybdenite, azurite, chalcocite, and covellite in bedrock and their absence in till are related to one or more of the following factors: i) bedrock exposed to glacial erosion did not contain these minerals; ii) these minerals were present in bedrock exposed to glacial erosion but were not abundant enough to be detected in a ca. 10 kg bulk till sample; iii) minerals were comminuted by glacial processes to fine particles not identified as part of the heavy mineral identification procedure; or iv) minerals were present in till but were oxidized and destroyed during in situ, post glacial weathering.

Pyrite is common in porphyry Cu deposits (Sinclair, 2007; Sillitoe, 2010), including

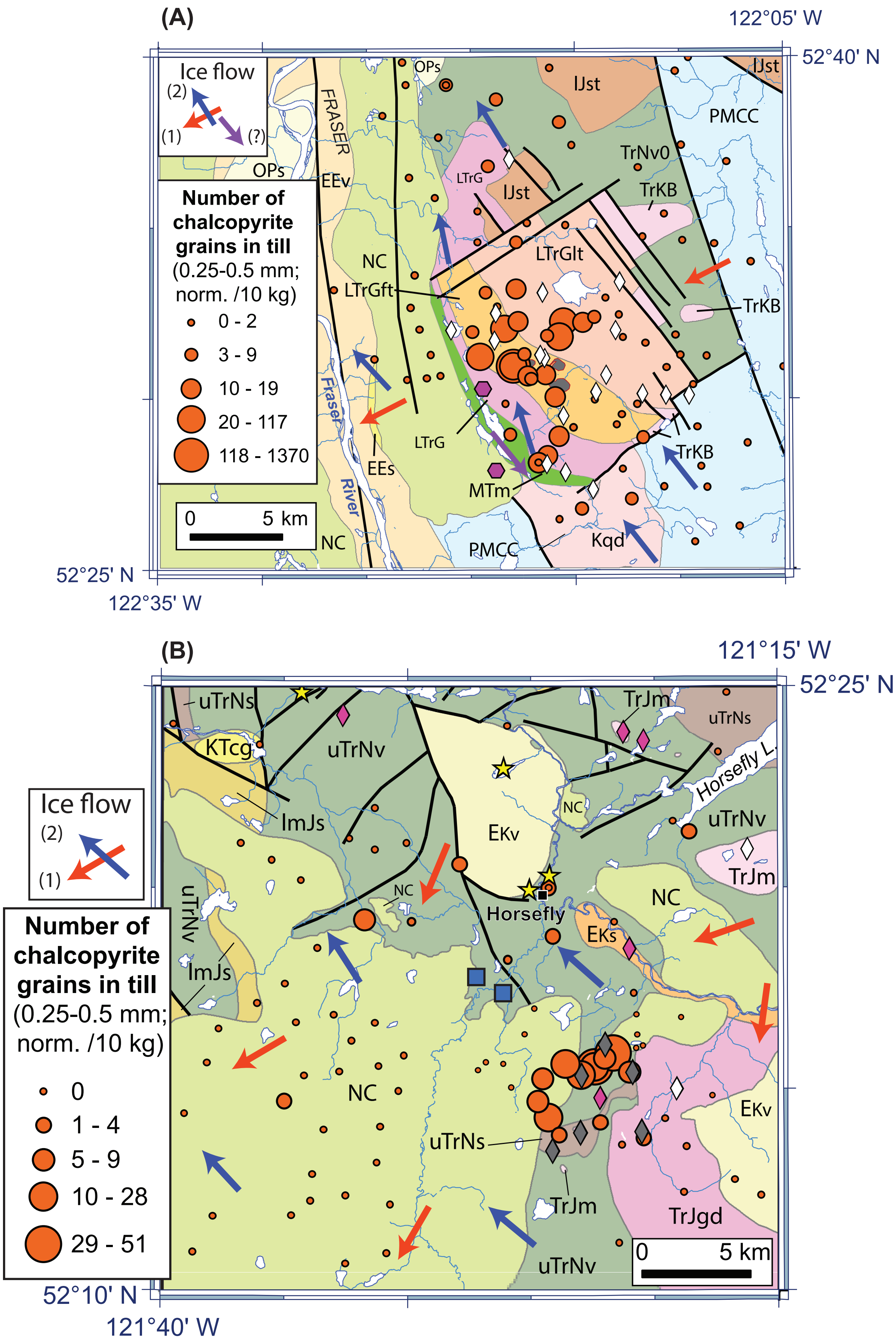

Figure 7. Distribution of chalcopyrite in till at the (A) Gibraltar deposit and (B) Woodjam prospect. Figure modified from Plouffe et al. (2016) and Plouffe and Ferbey (2017). Data from Plouffe and Ferbey (2016). See figures 2 and 4 for bedrock geology legend.

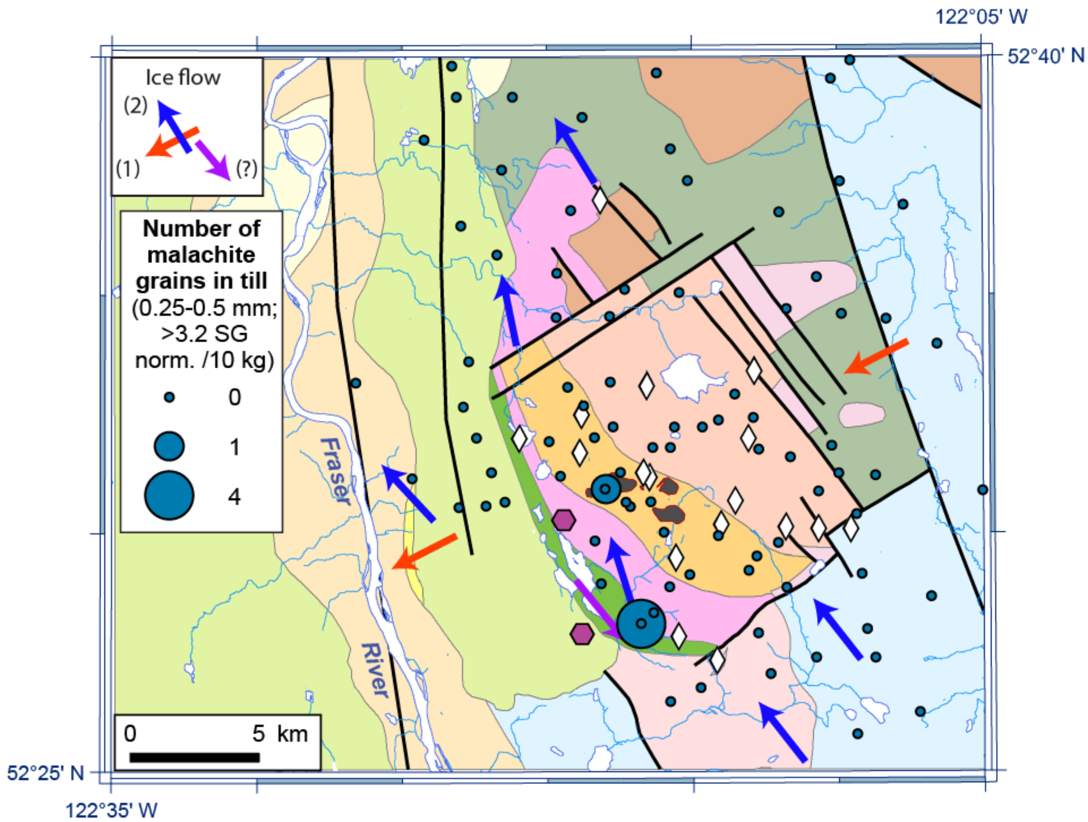

Figure 8. Distribution of malachite in till at the Gibraltar deposit. Data from Plouffe and Ferbey (2016). See Figure 2 for bedrock geology legend.

Gibraltar and Woodjam. It was present in all mineralized bedrock samples examined in our study (Tables 1 and 2). Till contains abundant pyrite (>47 pyrite grains per 10 kg) down-ice (southwest and southeast) of the ore zones at Gibraltar (Fig. 9A). The regional distribution of pyrite in till at Woodjam does not show greater abundance near the mineralized zones (Fig. 9B). Given the wide range of potential geological sources for pyrite, its abundance by itself in till or other surficial sediments is not an indication of porphyry Cu mineralization unless it is found in association with other PCIM.

Gold grains in till can be indicator minerals of Cu-Au porphyry mineralization (Hashmi et al., 2015; Plouffe et al., 2016). There is no gold at Gibraltar and the regional distribution of gold grains in till in this region likely reflects variability in the regional background content: 0 to 22 grains/10 kg (Fig. 10). As indicated above, gold grains were recovered from the Woodjam bedrock samples (Table 1). However, the gold grain distribution in till does not reflect the presence of Au in the Woodjam deposits (Fig. 10). Most till samples with more than 8 gold grains per 10 kg are in the region of Neogene Chilcotin basalt west of Woodjam where there is no known Au source in the bedrock. There, the gold in till could be derived from the reworking of pre-glacial placer deposits (Ferbey and Plouffe, 2014; Plouffe and Ferbey, 2017).

Potential PCIM have been identified in till of the Gibraltar and Woodjam areas but were absent in bedrock samples used for this study. It is possible that bedrock samples that were examined in this study were too small or that not enough bedrock from all mineralized and altered zones were included in this study to account for

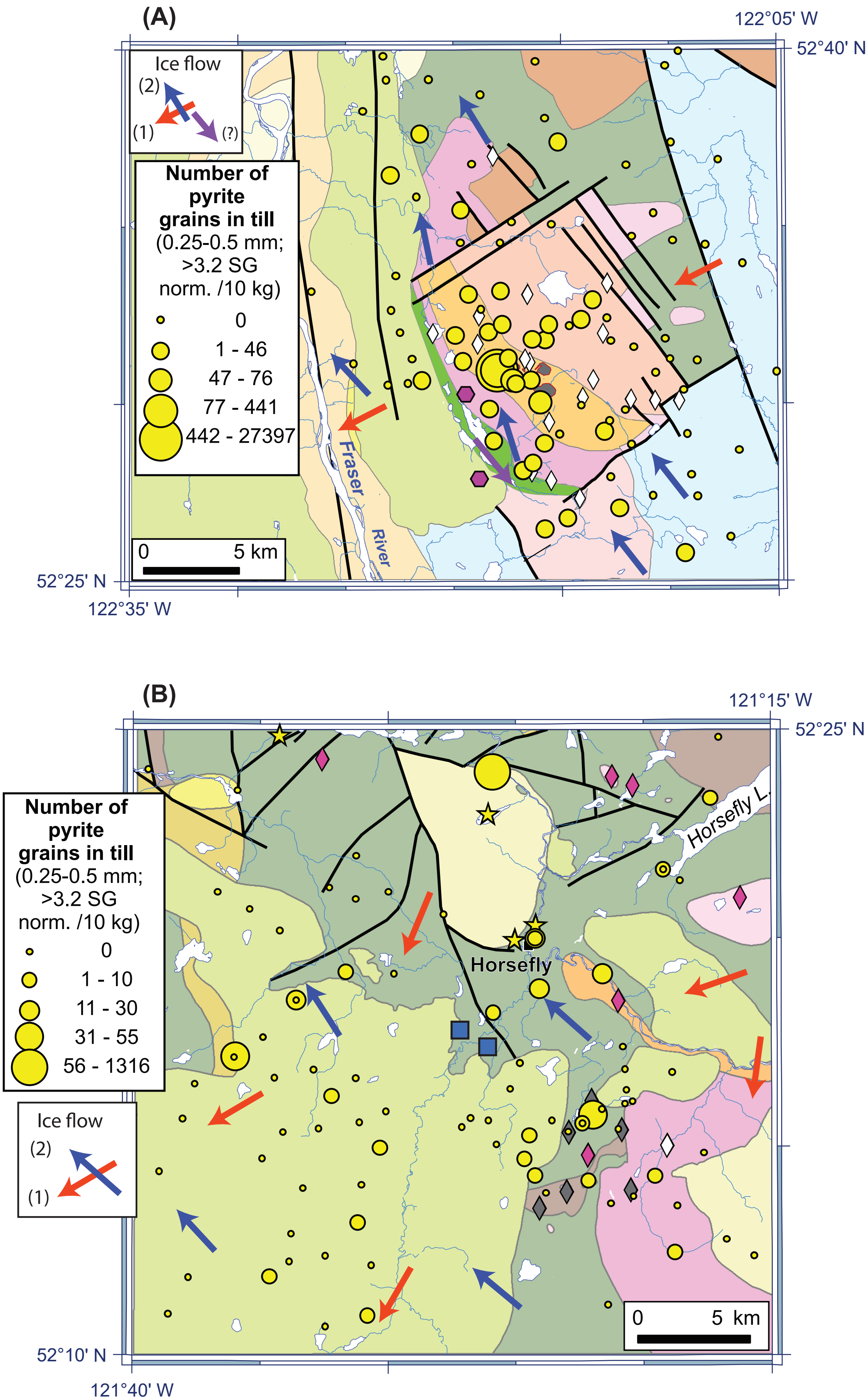

Figure 9. Distribution of pyrite in till at the (A) Gibraltar deposit and (B) Woodjam prospect. Data from Plouffe and Ferbey (2016). Figure modified from Plouffe and Ferbey (2017). See figures 2 and 4 for bedrock geology legends.

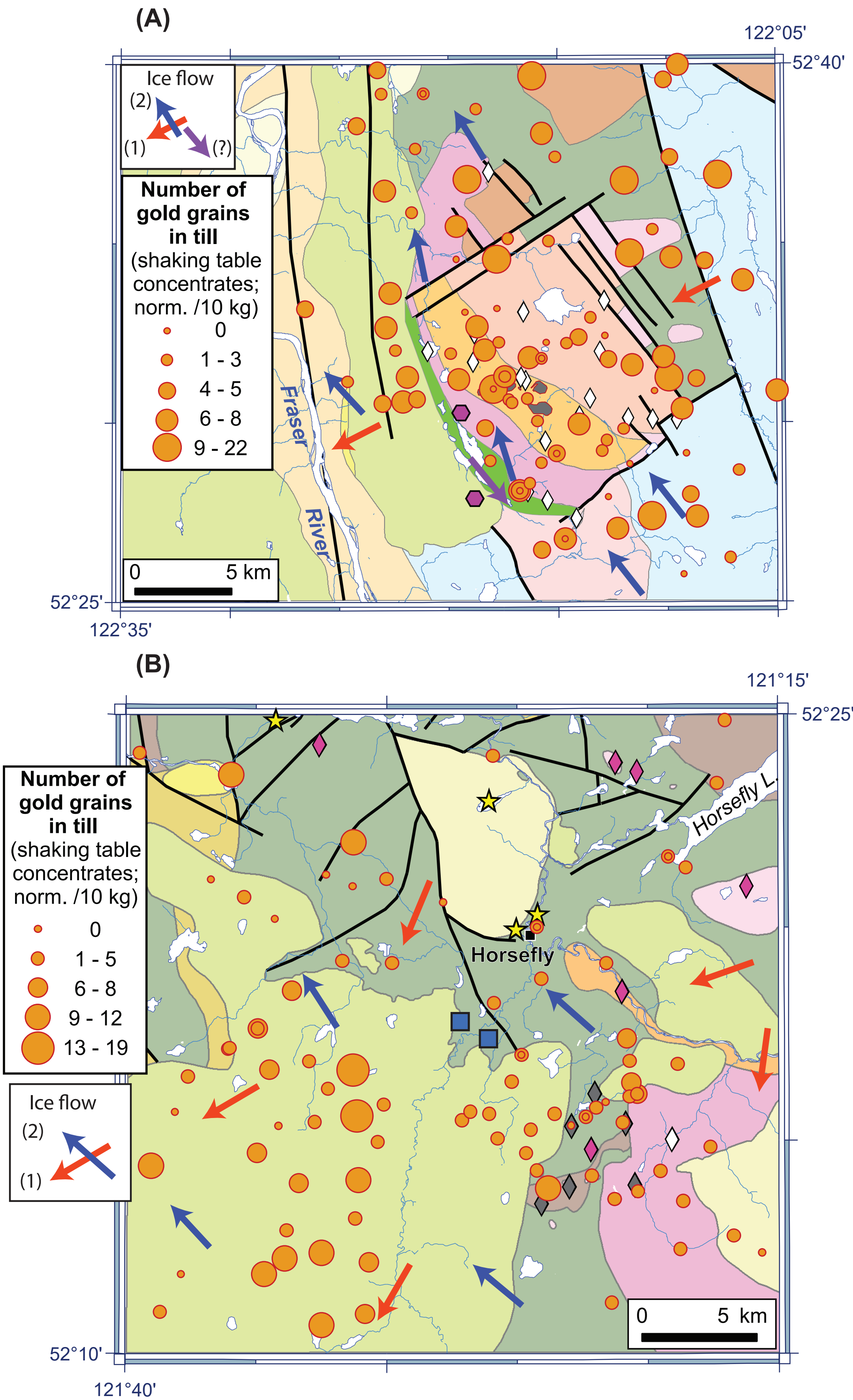

Figure 10. Distribution of gold grains in till at the (A) Gibraltar deposit and (B) Woodjam prospect. Data from Plouffe and Ferbey (2016). Figure modified from Plouffe and Ferbey (2017). See figures 2 and 4 for bedrock geology legends.

the full mineral assemblage of low-grade, large tonnage, porphyry Cu-Mo mineralization such as at Gibraltar and Woodjam. However, it is also possible that these potential PCIM have a different bedrock source altogether. A few examples of potential PCIM identified in till follow.

Rutile (TiO_2; 4.25 SG) has been investigated as a PCIM by Williams and Cesbron (1977), Force et al. (1984), Scott (2005), and Rabbia et al. (2009) amongst others, and is present in till in the Gibraltar and Woodjam areas (Plouffe and Ferbey, 2016, 2017; Wolfe, 2017) (Fig. 11). It is reported as an accessory mineral in the mine phase tonalite (mineralized intrusive phase) of the Granite Mountain batholith at Gibraltar (Bysouth et al., 1995; Kobylinski et al., 2016) but is not reported to be present in the rocks at Woodjam (Sherlock and Trueman, 2013; Sherlock et al., 2013). It was not recovered from bedrock samples examined in this study. The rutile reported in till is red which could be diagnostic of porphyry Cu mineralization (e.g., Williams and Cesbron, 1977; Averill, 2007), but its spatial distribution and abundance does not appear to be related to known porphyry Cu-Mo mineralization (Fig. 11). The composition of red rutile in till at Gibraltar was investigated by Wolfe (2017). Some grains do contain >10 ppm Sb and >1 ppm Mo similar to concentrations observed in rutile of the El Teniente porphyry Cu deposit in Chile (Rabbia et al., 2009; Plouffe et al., 2018).

Jarosite [($KFe_3(SO_4)_2(OH)_6$; 3.25 SG], a weathering product of pyrite and chalcopyrite in a leached cap or supergene horizon (Averill, 2007, 2011; Kelley et al., 2011), is present in till at Gibraltar (1-69 grains/10 kg) and Woodjam (1-5455/10 kg) with greater abundance near the mineralized zones compared to background regions (Fig. 12). A similar relationship between jarosite in till and mineralization exists at the Pebble porphyry Cu-Au-Mo deposit (Kelley et al., 2011). Jarosite was not identified in the bedrock samples because none were from leached cap or supergene zones. However, supergene enrichment is present and generally weak (1-3 m thick) at Gibraltar except over Gibraltar East, where it has been protected from glacial erosion in a down-faulted block (Bysouth et al., 1995; van Straaten et al., 2013). This down-faulted block is a potenital source of jarosite in till. Supergene enrichment was not reported at Woodjam (Sherlock and Trueman, 2013; Sherlock et al., 2013). However, abundance of jarosite in till overlying and in the periphery of the mineralized zones at Woodjam is much higher than at Gibraltar. See also Plouffe and Ferbey (2017) for more examples of jarosite distribution in till near porphyry mineralisation.

A broad region with high tourmaline [$XY_3Z_6(T_6O_{18})(BO_3)_3V_3W$; 3.0-3.2 SG, >3.2 SG with high Fe content] grain counts in till (>49 grains/10 kg; 0.25-0.5 mm; 2.8-3.2 SG) extends to the west and north of the mineralized zones at Woodjam (Fig. 13). These tourmaline grain counts for the 2.8-3.2 SG fraction are considered partial because they exclude any tourmaline present in the >3.2 SG fraction. Tourmaline was absent from our bedrock samples, but is known to occur in alteration zones at Deerhorn and Takom (Fig. 5) (Sherlock and Trueman, 2013; Sherlock et al., 2013; Chapman et al., 2015). Following a classification scheme established by Baksheev et al. (2012), Chapman et al. (2015) showed that tourmaline in till <1 km down-ice of Deerhorn has a major element composition (Fe, Mg, Al) indicative of a porphyry Cu source. At Gibraltar, tourmaline is not reported in the alteration zones and its distribution in till does not reflect known porphyry Cu mineralized zones (Fig. 13). The composition of tourmaline in bedrock and till is being further investigated at Woodjam (McClenaghan et al., 2018; Becket-Brown et al., 2019)

Apatite [$A_5(XO_4)_3$(F,Cl,OH); 3.17-3.23 SG], present as an accessory mineral in a number of mineral deposit types, can have a composition that is diagnostic of a porphyry Cu source (Bouzari et al., 2016; Mao et al., 2016, 2017; Rukhlov et al., 2016). None of our bedrock samples from Gibraltar contained apatite, but up

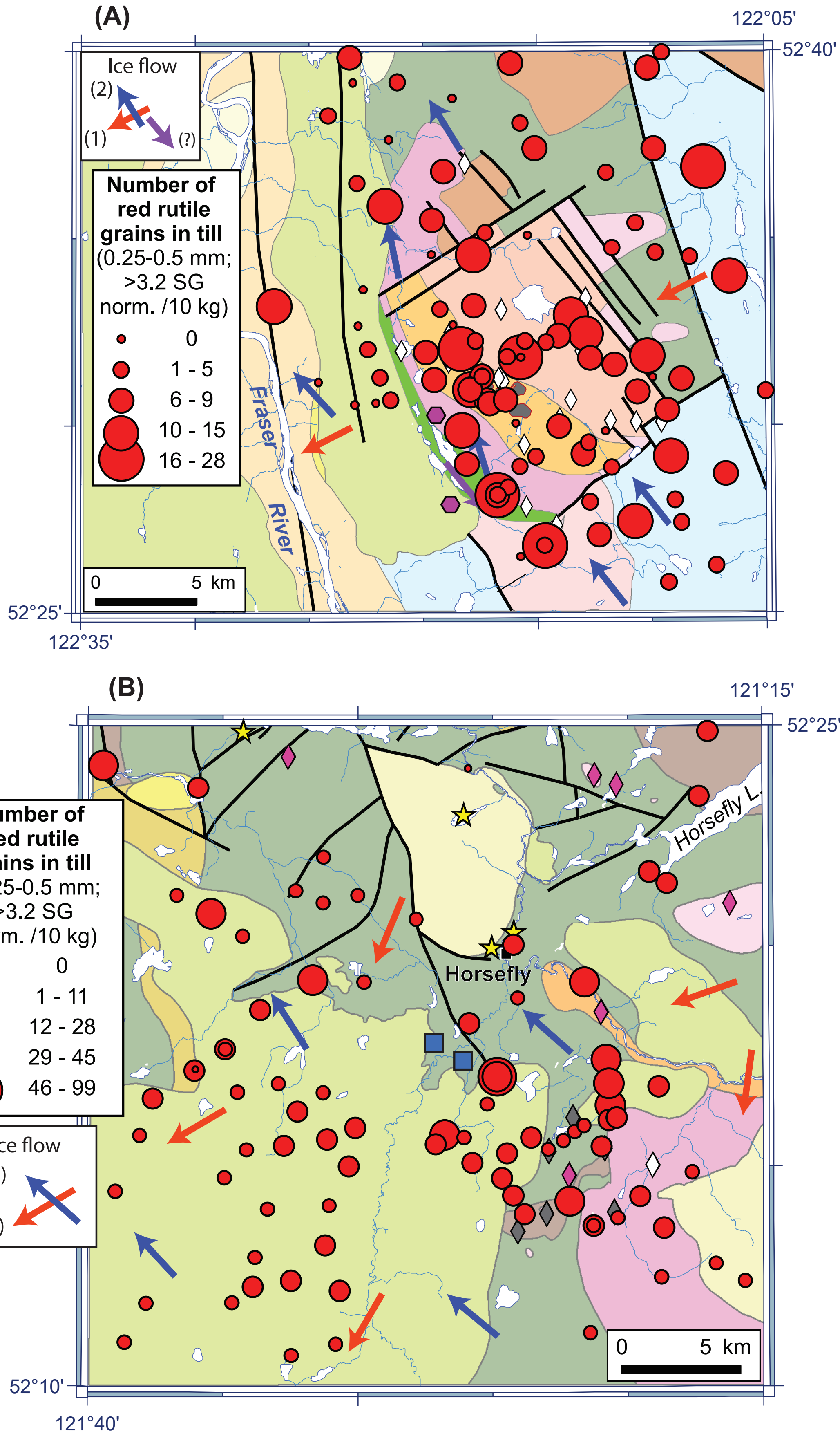

Figure 11. Distribution of red rutile in till at the (A) Gibraltar deposit and (B) Woodjam prospect. Data from Plouffe and Ferbey (2016). Figure modified from Plouffe and Ferbey (2017). See figures 2 and 4 for bedrock geology legends.

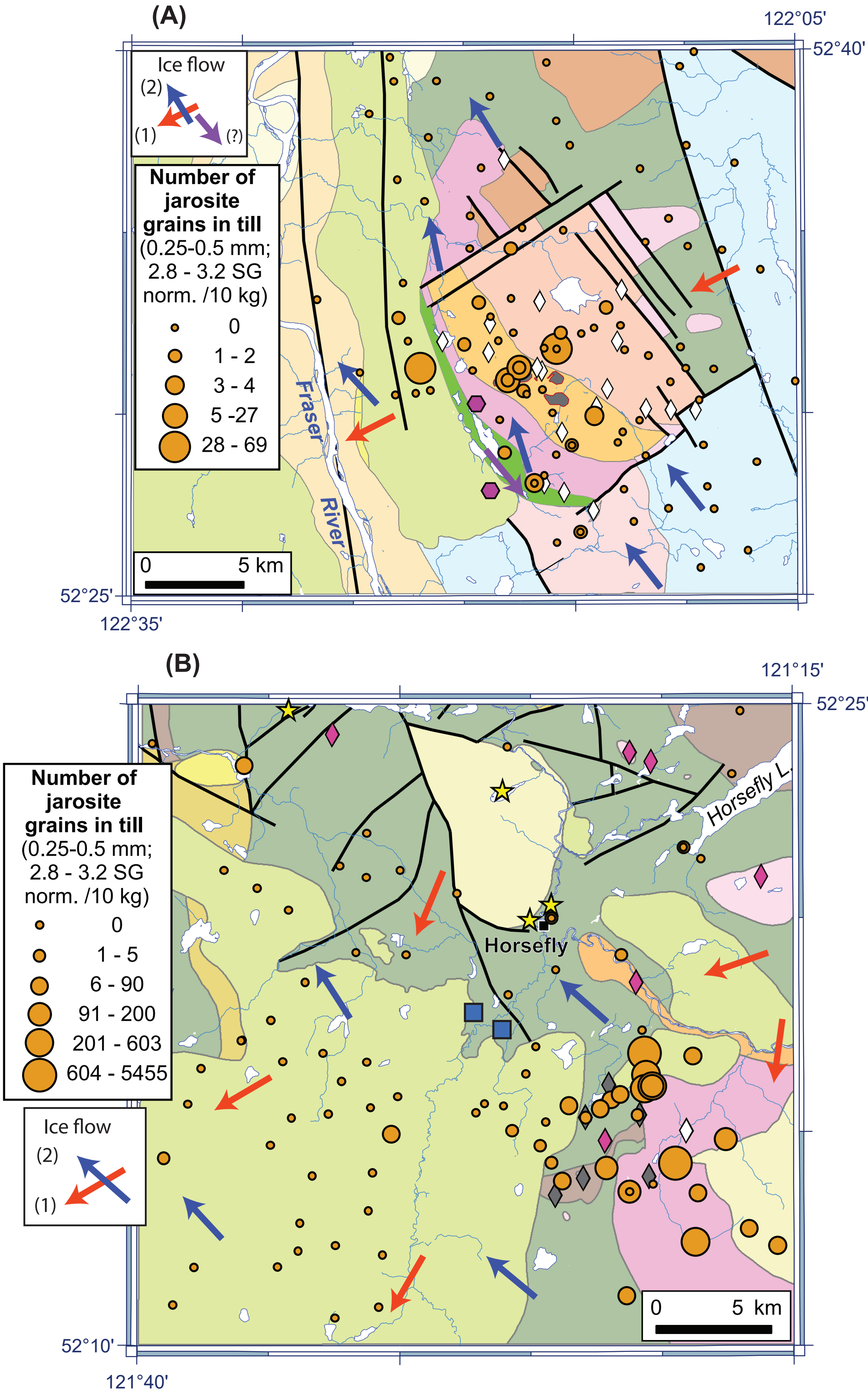

Figure 12. Distribution of jarosite in till at the (A) Gibraltar deposit and (B) Woodjam prospect. Data from Plouffe and Ferbey (2016). Figure modified from Plouffe and Ferbey (2017). See figures 2 and 4 for bedrock geology legends.

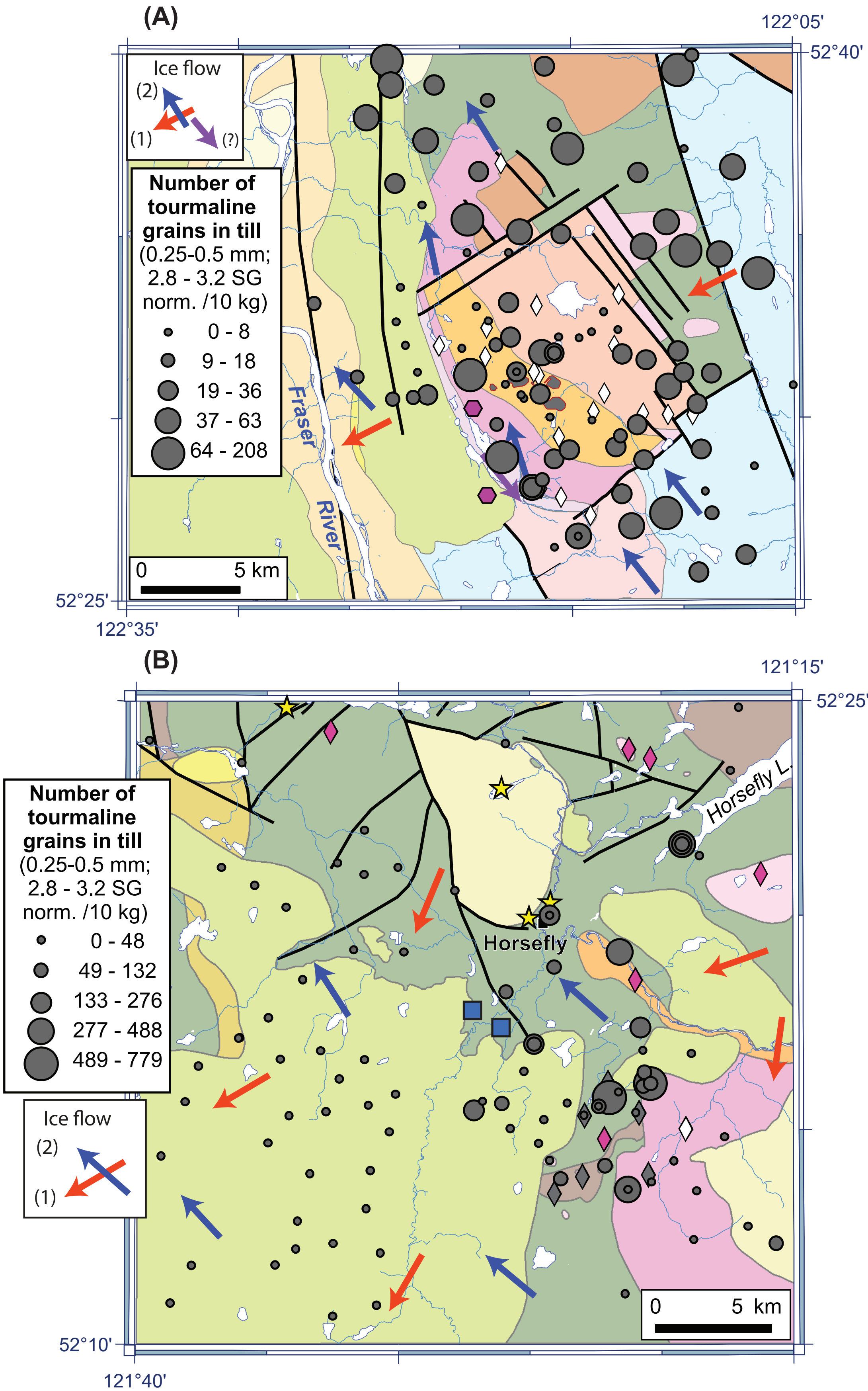

Figure 13. Distribution of tourmaline in till at the (A) Gibraltar deposit and (B) Woodjam prospect. Data from Plouffe and Ferbey (2016). Figure modified from Chapman et al. (2015) and Plouffe and Ferbey (2017). See figures 2 and 4 for bedrock geology legends.

to 3% apatite was recovered in the 0.25-0.5 mm, >3.2 SG, >1 amp fraction of Woodjam samples (Appendix 5). Rukhlov et al. (2016) have recovered and analyzed apatite from till and bedrock at Gibraltar and Woodjam. At both sites, they identified apatite grains in till that have a porphyry mineralization signature. However, the abundance of apatite in till by itself did not indicate the presence of porphyry Cu mineralization (See Fig. 3 for Gibraltar and Fig. 5 for Woodjam in Rukhlov et al., 2016, and Fig. 14 in Plouffe and Ferbey, 2017). As with tourmaline, the reported abundance of apatite in till is a partial count as these counts were on the >3.2 SG fraction excluding any less dense apatite with <3.2 SG (Plouffe and Ferbey, 2016).

Table 3 summarizes the potential PCIM present in till and bedrock at Gibraltar and Woodjam. Given the nature and extent of the mineralization and alteration zones, and our limited number of bedrock samples, this list is not considered exhaustive.

Table 3. Summary of mineral abundances in bedrock and till at Gibraltar and Woodjam; in the 0.25-0.5 mm size fraction unless indicated otherwise; >3.2 and 2.8-3.2 SG

Minerals	**GIBRALTAR**		**WOODJAM**	
	Bedrock gr/1 kg	Till gr/10 kg	Bedrock gr/1 kg	Till gr/10 kg
Chalcopyrite	2 to 381,056 [1]	0 to 1,370 [2, 3]	0 to 6,061[1]	0 to 51 [2, 3]
Azurite	0 to 27 [1]	None[2]	Present[4]	None[2]
Chalcocite	0 to 108,873 [1]	None[2]	0 to 3[1, 4]	None[2]
Malachite	0 to 46,261 [1]	0 to 4 [2]	Present[4]	None[2]
Bornite*	Present[5]	None[2]	0 to 147 [1]	None[2]
Native Cu*	Present[5]	None[2]	0 to 1[1]	None[2]
Covellite	0 to 8 [1]	None[2]	Present[4]	None[2]
Pyrite	0 to 275,103 [1]	0 to 27,400 [2]	7 to 21,337[1]	0 to 1,316 [2]
Molybdenite	0 to 41,265 [1]	None[2]	0 to 3 [1]	None[2]
Rutile	Present[5, 6]	0 to 28 [2]	None[1, 4]	0 to 99 [2]
Jarosite	None[1, 5]	0 to 69 [2]	None[1, 4]	0 to 5,455 [2]
Tourmaline	None[1, 5]	0 to 208[2]	Present[4, 7]	0 to 779[2, 7]
Apatite	Present[8]	0 to trace [2, 8]	Present[8]	0 to trace [2, 8]
Gold*	0 to 5[1]	0 to 22[2]	0 to 98[1]	0 to 19[2]

* - mineral observed in the shaking table concentrate; <0.25 mm

1- This study
2- Plouffe and Ferbey (2016, 2017)
3- Plouffe et al. (2016)
4- Sherlock et al. (2013); Sherlock and Trueman (2013)
Trace - <0.5%; no reported grain count
5-Bysouth et al. (1995); van Straaten et al. (2013)
6-Kobylinski et al. (2016)
7-Chapman et al. (2015)
8-Rukhlov et al. (2016)

Conclusions

A comparison of the bedrock heavy mineral assemblage with that of till at the Gibraltar porphyry Cu-Mo deposit and Woodjam porphyry Cu-Au-Mo prospect, allows the following observations.

1. Chalcopyrite, the main Cu ore mineral at these sites, is abundant in bedrock and till, and is therefore a key PCIM (see also Hashmi et al., 2015, Plouffe et al., 2016, and Plouffe and Ferbey, 2017).

2. Molybdenite, the main Mo ore mineral, native Cu, and other Cu minerals such as malachite, azurite, chalcocite, bornite, and covellite, are in bedrock but are rare to absent in till. Possible reasons for this include: i) bedrock exposed to glacial erosion did not contain these minerals; ii) these minerals were present in bedrock exposed to glacial erosion but were not abundant enough to be detected in a ca. 10 kg bulk till sample; iii) minerals were comminuted by glacial processes to particles smaller than the size fractions examined in this study (i.e. ca. 25 to 50 µm in the pan concentrate); or iv) minerals were present in till but were destroyed during post glacial weathering of the till. These minerals are expected to be rare in till, but when found, their presence can be significant.

3. Jarosite, a mineral typically found in leached cap and supergene enrichment zones, is generally more abundant in till near the known mineralized zones compared to surrounding regions and therefore, should be considered a PCIM diagnostic of the oxidized portion of porphyry mineralization. None of the processed bedrock sample were from supergene zone or leached cap. Therefore, they did not contain jarosite.

4. Tourmaline, apatite and rutile are present in till at both study sites. Tourmaline occurs in bedrock at Woodjam, rutile at Gibraltar, and apatite at both sites. The composition of tourmaline and apatite in till can be diagnostic of porphyry Cu mineralization (Chapman et al., 2015; Rukhlov et al., 2016). At Gibraltar, rutile in till with >10 ppm Sb and >1 ppm Mo could be derived from local mineralized zones (Wolfe, 2017; Plouffe et al., 2018).

Given the inherent variability in the mineralogy of porphyry Cu mineralization and associated alteration zones, a mineral exploration program should seek to recover an extensive suite of potential PCIM in till or other surficial media (such as stream sediments) (Plouffe and Ferbey, 2017). Combining indicator mineral abundance with till geochemistry will provide additional information to identify covered porphyry Cu mineralization (Hashmi et al., 2015; Plouffe et al., 2016; Plouffe and Ferbey, 2017).

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