

Porphyry Indicator Minerals (PIMs) from Alkalic Porphyry Copper-Gold Deposits in South-Central British Columbia (NTS 092, 093)

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Introduction

The common occurrence of resistate minerals in mineralized and altered portions of British Columbia's alkalic porphyry copper deposits suggests that these minerals can be utilized as indicators of mineralization and used for exploration in terrains covered by glacial till. Porphyry indicator minerals (PIMs) have been shown to have unique physical and chemical characteristics, which emphasize their potential application to the exploration of concealed deposits in BC (Bouzari et al., 2011).

Porphyry indicator minerals are chemically stable in weathered environments, have a high specific gravity, are sufficiently coarse-grained and display characteristic features, all of which can directly link them to a porphyry-related alteration assemblage. These minerals typically display unique physical properties, such as colour, size and shape, which allow their presence to be used as a prospecting tool in a manner similar to that in which kimberlite indicator minerals (KIMs) are used. Moreover, the chemical compositions of PIMs can further identify and confirm mineralizing environments that relate directly to specific alteration zones in porphyry systems. Although easy to collect in heavy-mineral concentrates, these PIMs have rarely been used in porphyry exploration. Therefore, by evaluating the presence, abundance, relative proportions and compositions of PIMs from surficial materials, it is possible to follow-up geophysical and stream-sediment geochemical anomalies, which can act as vectors toward concealed alkalic porphyry copper deposits in highly prospective terranes, such as Quesnellia and Stikinia, in central BC. The purpose of this project is to identify the occurrence, types,

relative amounts and compositions of selected PIMs in several alkalic porphyry deposits in order to elucidate important PIM signatures.

The main objectives of this research are to

- determine assemblages and occurrence of indicator minerals within different alteration and mineralization types of selected BC alkalic porphyry Cu-Au deposits;
- determine the diagnostic physical parameters and chemical compositions of indicator minerals, particularly apatite, garnet, magnetite and diopside; and
- establish criteria for use of resistate minerals as an exploration tool for alkalic porphyry deposits in south-central BC

This report summarizes results of fieldwork and sampling from the Mount Polley, Mount Milligan and Copper Mountain deposits in BC during August and October 2012; sampling at the Lorraine deposit is planned for 2013. Preliminary observations on the alteration assemblages and resistate minerals from each site are presented.

Alkalic Porphyry Deposits in BC

Cordilleran porphyry deposits have a diverse anatomy, as well as mineralization and alteration styles. These deposits formed during two separate time intervals: Late Triassic to Middle Jurassic and Late Cretaceous to Eocene. The Early Mesozoic deposits formed either during or after Late Triassic arc formation in the Quesnel and Stikine terranes, and prior to terrane accretion onto the North American continent (McMillan et al., 1995); they include associations with both calcalkalic and alkalic igneous rocks. Calcalkalic varieties include the Island Copper Cu-Mo-Au deposit, and the Highland Valley, Kemess and Gibraltar Cu-Mo deposits (McMillan et al., 1995). The alkalic Cu-Au deposits include Galore Creek, Mount Polley, Mount Milligan and Copper Mountain. Younger Late Cretaceous to Eocene por-

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phyry deposits formed in an intracontinental arc setting after the accretion and assembly of the Cordilleran terranes; they are mostly related to calcalkaline magmatism and examples include the Granisle porphyry Cu-Au(\pm Mo) deposit and Endako porphyry Mo deposits. Only Early Mesozoic alkalic porphyry deposits were selected for this study; these are the Mount Polley, Mount Milligan, Copper Mountain and Lorraine deposits (Figure 1).

Alteration Assemblages and Resistate Minerals

Alkalic porphyry deposits are generally characterized by small-volume pipe-like intrusions, a medium to relatively small areal extent and a lack of advanced argillic alteration. Phyllic alteration is restricted to fault zones and evidence of

connection to high-sulphidation epithermal deposits is not commonly observed (Chamberlain et al., 2007). A Late Triassic to Early Jurassic magmatic arc defines two suites of alkalic intrusions, silica-saturated and silica-undersaturated, both hosting Cu-Au porphyry deposits in BC. Silica-undersaturated-intrusion suites are locally zoned and their composition varies from pyroxenite to syenite. Their mineralogy is characterized by variable amounts of aegirine-augite, K-feldspar, biotite, titanite, apatite, melanitic garnet, hornblende, plagioclase and magnetite (Lueck and Russell, 1994). The silica-saturated-intrusion suites vary from diorite to monzonite and their mineralogy is characterized by variable amounts of augite, biotite, magnetite, plagioclase, K-feldspar and apatite; hornblende and titanite are less common, and quartz is rare (Table 1; Lueck and Russell, 1994).

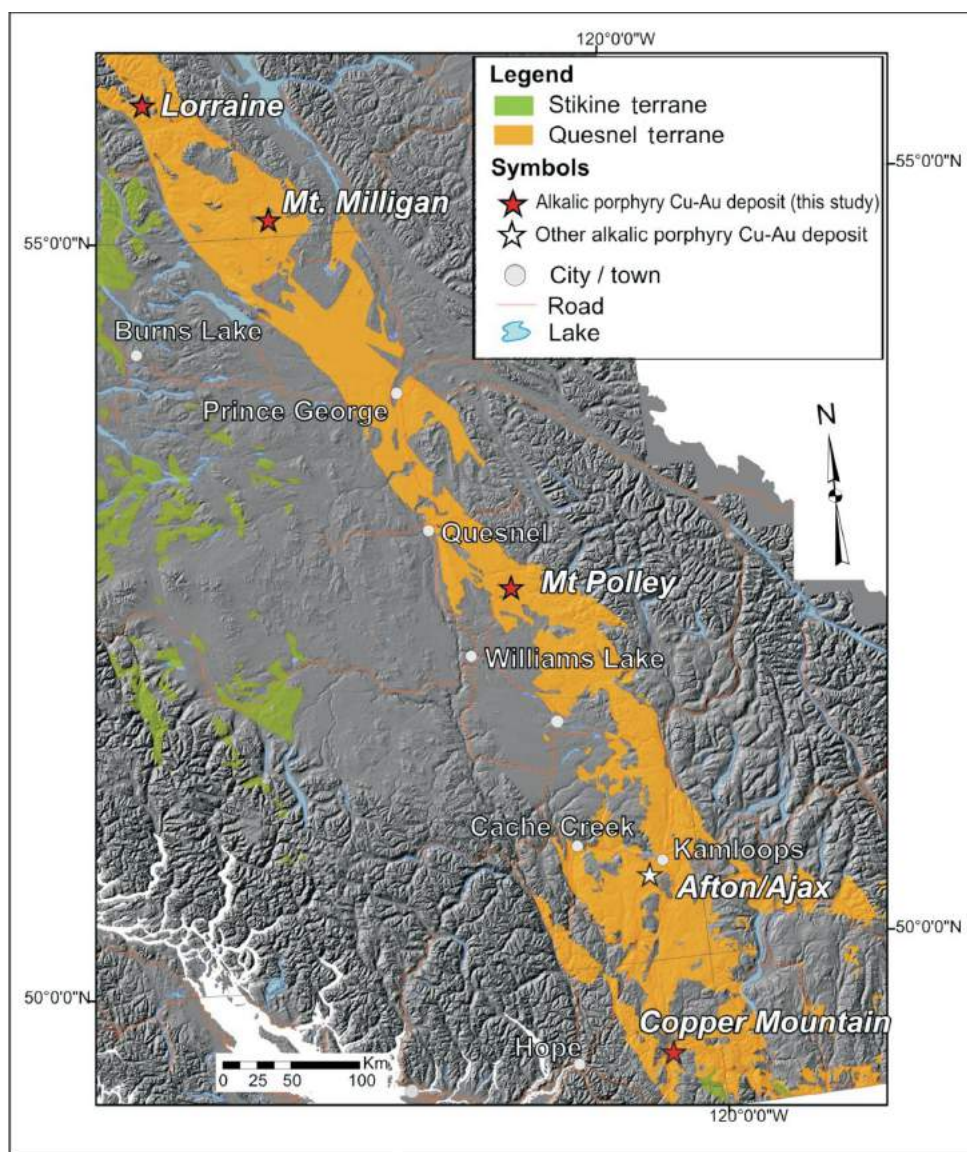


Figure 1. Digital elevation map showing Triassic and Early Jurassic Quesnel and Stikine terranes of central-south British Columbia and location of selected deposits (modified from Bissig et al., 2010).

Field and Analytical Methods

Sampling

Fieldwork and sampling were carried out at the Mount Polley, Mount Milligan and Copper Mountain porphyry copper deposits during August and October 2012. These deposits represent both silica-saturated and silica-undersaturated classes of alkalic porphyry deposits. A total of 49 rock samples were collected from the three sites. The main purpose of the initial sampling survey was to characterize the resistate minerals that occur with each alteration assemblage. Core samples (~30 cm long) were collected from both altered and unaltered rock units at each site in order to determine which resistate-mineral phases are indicators for copper mineralization. Larger (2–4 kg) hand specimens were also collected from outcrops, as well as open-pit benches, for heavy-mineral separation. Glacial-till samples (10–15 kg) were collected from Mount Polley (n=5) and Mount Milligan (n=7). These samples were taken from glacial sediments at or near the mine sites. The objective of till sampling was to identify the fraction and occurrences of PIMs in glacial till, which partly covers the deposit. Results will be compared with the bedrock heavy-mineral separates in a future publication.

Methods

A wide range of analytical techniques are being utilized to characterize the physical and chemical properties of resistate minerals, with emphasis on physical properties such as shape, size, dimensions, color, luminescence and infrared and ultraviolet spectroscopic properties. Selected mineral species will be analyzed for their trace-element composition to characterize and differentiate barren from mineralized systems. Representative till sediments will be analyzed to study the effects of transport and distribution of PIMs. Initial activity consists of petrographic work on core samples, hand specimens and thin polished sections of bedrock materials in order to characterize the in situ abundance and physical properties of indicator minerals.

Preliminary Observations

Mount Polley

Mount Polley is centred within and surrounds several diorite to monzonite (Figure 2a, b) intrusions with associated igneous breccia bodies. Alteration at Mount Polley consists of three concentrically-zoned alteration assem-

blages (Fraser et al., 1995): a potassic core (Figure 2c) surrounded by a garnet-epidote zone with minor magnetite (Figure 2d) and an outer propylitic rim. The potassic core has been further divided into three distinct zones: an actinolite (250 m wide), a biotite (100 m wide) and a K-feldspar-albite (1 km wide) zone (Hodgson et al., 1976; Bailey and Hodgson, 1979). Apatite (Figure 3a) and titanite (Figure 3b) occur in small amounts as accessory minerals, whereas magnetite is massive (Figure 3c) and widely distributed within the potassic core. An outer ‘green alteration’ rim is observed in peripheral parts of the deposit and includes a mineral assemblage of epidote, chlorite with calcite veins and variable amounts of disseminated pyrite (Figure 2e).

Mount Milligan

Mount Milligan consists of three main monzonite stocks (Figure 4a, b) of Middle Jurassic age (MBX, South Star and Rainbow dike) hosted within the Late Triassic Takla Group volcanic sequence (Sketchley et al., 1995; Jago and Tosdal, 2009). Two alteration patterns are recognized: a zone of intense potassic alteration (Figure 4c), which consists of K-feldspar±biotite±magnetite, lies between the MBX stock and the Rainbow dike; lower temperature ‘green alteration’ (Figure 4d), consisting of epidote+chlorite+illite±pyrite, typically occurs below the footwall of the monzonitic Rainbow dike, where it overprints potassic alteration in volcanic hostrocks (Jago and Tosdal, 2009).

A fluid-flow alteration pattern affects the Takla volcanic sequence. These rocks have high permeability, allowing lateral migration of high-temperature magmatic fluids generating pervasive K-feldspar alteration of the volcanic rocks close to the stocks and ‘green alteration’ of epidote-chlorite-calcite veins and disseminated pyrite on the distal zones (Chamberlain et al., 2007).

Copper Mountain

The Copper Mountain deposit is centred on two principal Late Triassic intrusions, predominately of pyroxene diorite to monzonite and syenite (Figure 5a), hosted within the Triassic Nicola volcanic sequence (Stanley et al., 1992). Alteration patterns and assemblages at Copper Mountain consist of an early-stage pre-mineralization hornfels alteration, which is overprinted by sodic and potassic alteration. Hornfels alteration consists of the recrystallization of mafic and intermediate volcanic hostrocks, which is reflected by the presence of a dark purple, dark grey or black, fine-

Table 1. Characteristics of alkalic intrusions associated with porphyry deposits in south-central British Columbia (from Lang et al., 1995).

Alkalic porphyry types	Hostrock	Mineralogy	Resistate mineral	BC examples
Silica undersaturated	Pyroxenite to syenite	Aegirine-augite, biotite, plagioclase, K-feldspar, hornblende	Magnetite, garnet, apatite, titanite	Mount Polley, Lorraine, Galore Creek
Silica saturated	Diorite to monzonite	Augite, biotite, plagioclase, K-feldspar, hornblende	Magnetite, garnet, apatite, titanite	Mount Milligan, Copper Mountain

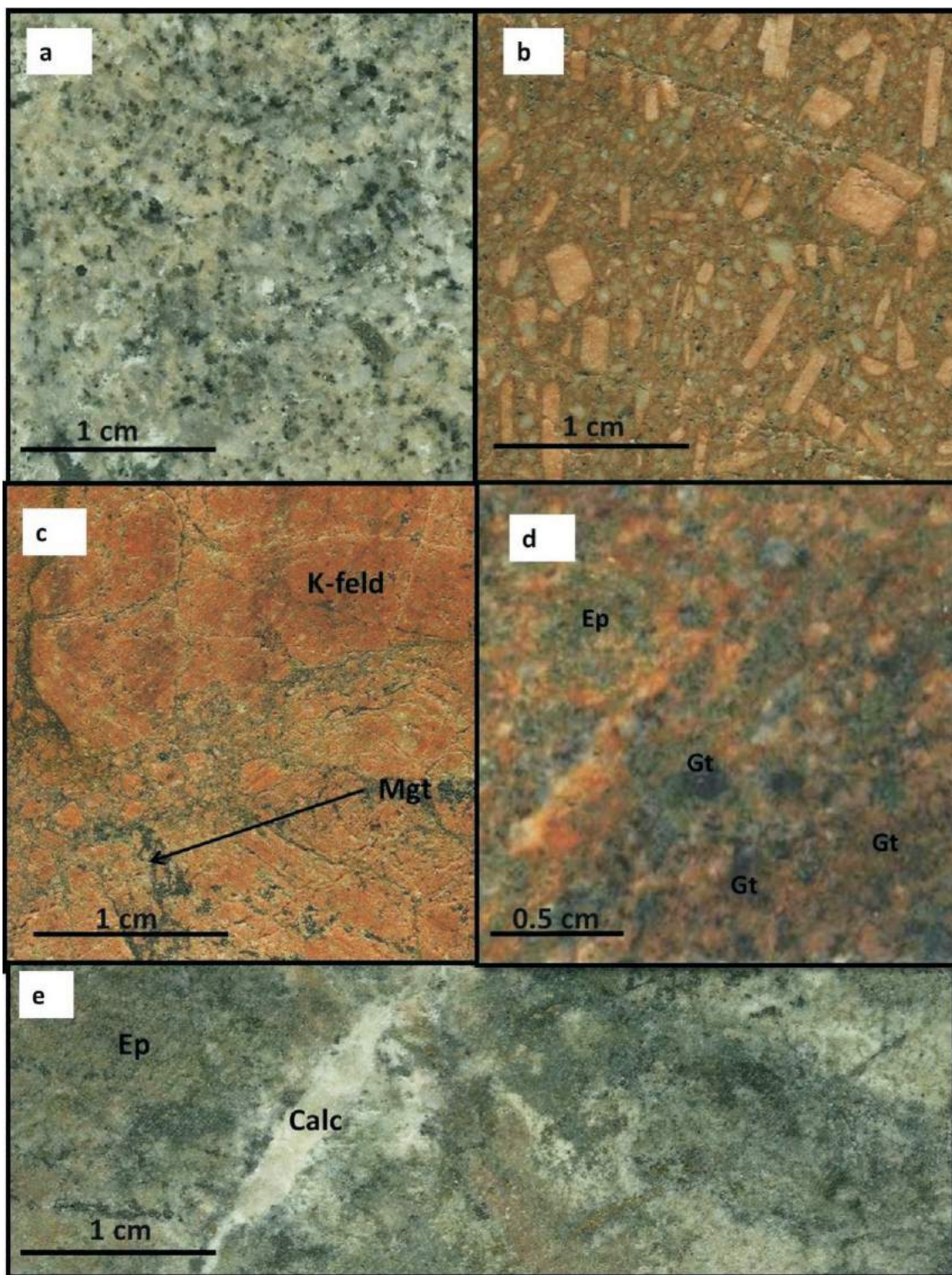


Figure 2. Photomicrographs of mineral assemblages of the Mount Polley deposit, south-central British Columbia, showing **a)** equigranular, medium-grained, light grey monzonite, with 30% K-feldspar, 60% plagioclase and 10% mafic minerals, taken from the road leading to the tailings (Polley_10, UTM Zone 10, 5822071N, 592687E; elevation 890 m); **b)** megacrystic porphyry from Wight pit (Polley_6, 5825240N, 592860E; elevation 921 m); **c)** pervasive K-feldspar alteration with narrow magnetite veinlets overprinting the original texture of the rock, sampled from Springer pit (SD12132-43m); **d)** garnet-epidote alteration assemblage overprinting potassic alteration, from Springer pit (SD12132-309m); **e)** 'green alteration' assemblage of epidote+chlorite±calcite±pyrite with characteristic green color, also from Springer pit, (SD12132-91m). Sample number followed by UTM co-ordinates are given for samples collected from outcrops; ore sample ID consists of hole number followed by depth. Abbreviations: Calc, calcite; Ep, epidote; Gt, garnet; K-feld, K-feldspar; Mgt, magnetite.

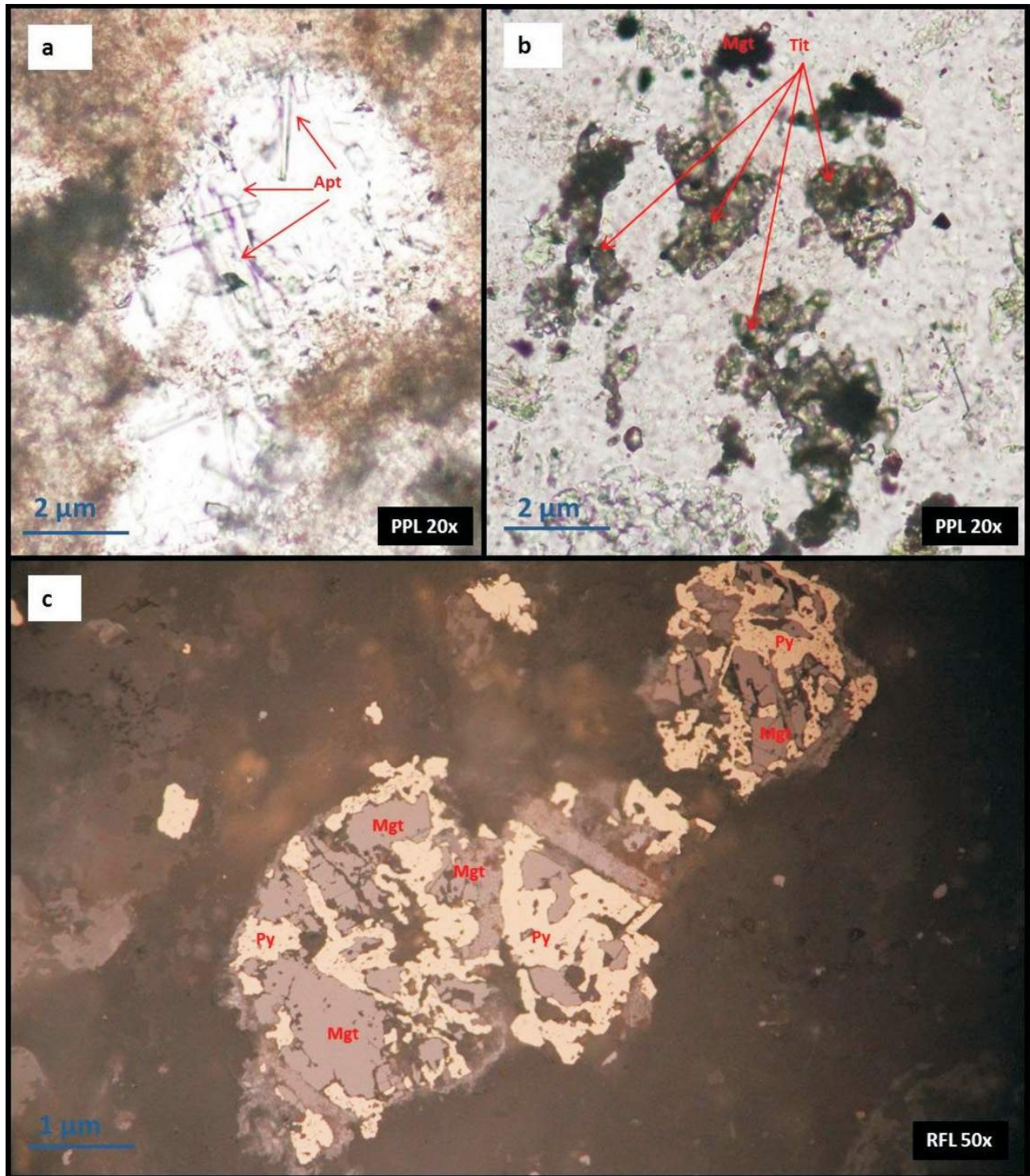


Figure 3. Photomicrographs of resistate minerals of the Mount Polley deposit, south-central British Columbia, showing **a)** apatite phenocrysts with long euhedral shapes, transparent in plan polarized light (PPL) as inclusions in a large altered-plagioclase phenocryst, from Springer pit (SD0981_92.3m); **b)** pale brownish titanite phenocrysts and very high relief in PPL intergrowth with magnetite phenocryst (Polley_12, UTM Zone 10 5825173N, 590993E; elevation 1052 m); **c)** abundant magnetite intergrowth with pyrite, from Wight pit (WB04102_237m). Sample number followed by UTM co-ordinates are given for samples collected from outcrops; core sample ID consists of hole number followed by depth. Abbreviations: Apt, apatite; Mgt, magnetite; Py, pyrite; Tit, titanite.

grained conchoidally fractured diopside+primary biotite+plagioclase+magnetite (Preto, 1972). Sodic alteration (Figure 5b) is restricted to the central portions of the deposit and is expressed as a bleached, typically pale greyish-green or mottled white and grey alteration of the host rock. It is characterized by albite after feldspar, by chlorite, epidote and diopside after mafic minerals, and by the partial destruction of magnetite (Stanley et al., 1992). Potassic alteration (Figure 5c) locally crosscuts zones of earlier sodic-calcic alteration and is widely distributed in the deposit; it is characterized by a pink K-feldspar-replacing plagioclase. Mafic mineral replacements by secondary biotite, epidote, calcite and minor chlorite are also characteristic of potassic alteration. In general, potassic alteration affects a larger total

volume of rock than sodic-calcic alteration; both alterations are characterized by high amounts of K-feldspar and mafic mineral replacement (Stanley et al., 1992).

A 'green alteration' assemblage (Figure 5d) of epidote+chlorite+calcite±pyrite typically occurs at the periphery of the deposit, replacing mafic minerals, but it may occur in the central parts along with the potassic alteration; it is generally dark to light or pale green and not texturally destructive. Plagioclase and K-feldspar replacement by albite+epidote+calcite is also common. Pyrite, hematite (specular) and subordinate magnetite locally occur (Stanley et al., 1992). However, it is possible that this alteration, which is mapped as pyrolytic at the mine, consists of several over-

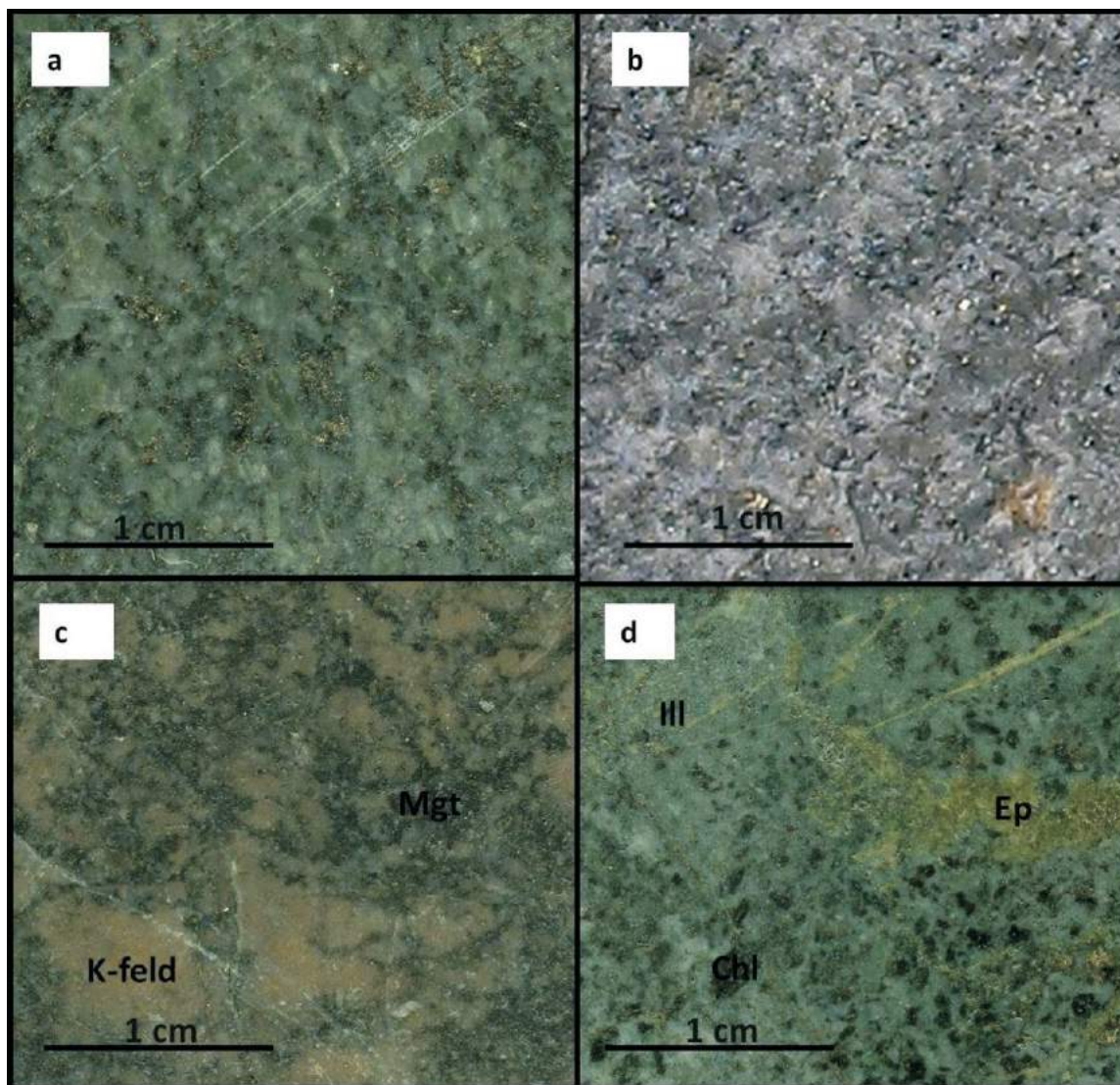


Figure 4. Photomicrographs of mineral assemblages of the Mount Milligan deposit, south-central British Columbia, showing **a**), equigranular, medium- to fine-grained, grey monzonite from the MBX stock (111015_286.1m); **b**) equigranular, medium-grained, pinkish-grey monzonite from the South Star stock (06_957_180m); **c**) potassic alteration assemblage of K-feldspar matrix with disseminated magnetite from the 66 Zone (07992-47m); **d**) 'green alteration' assemblage of epidote+chlorite+illite from the Southern Star stock (06957-212.7m). Core sample ID consists of hole number followed by depth. Abbreviations: Chl, chlorite; Ep, epidote; Ill, illite; K-feld, K-feldspar; Mgt, magnetite.

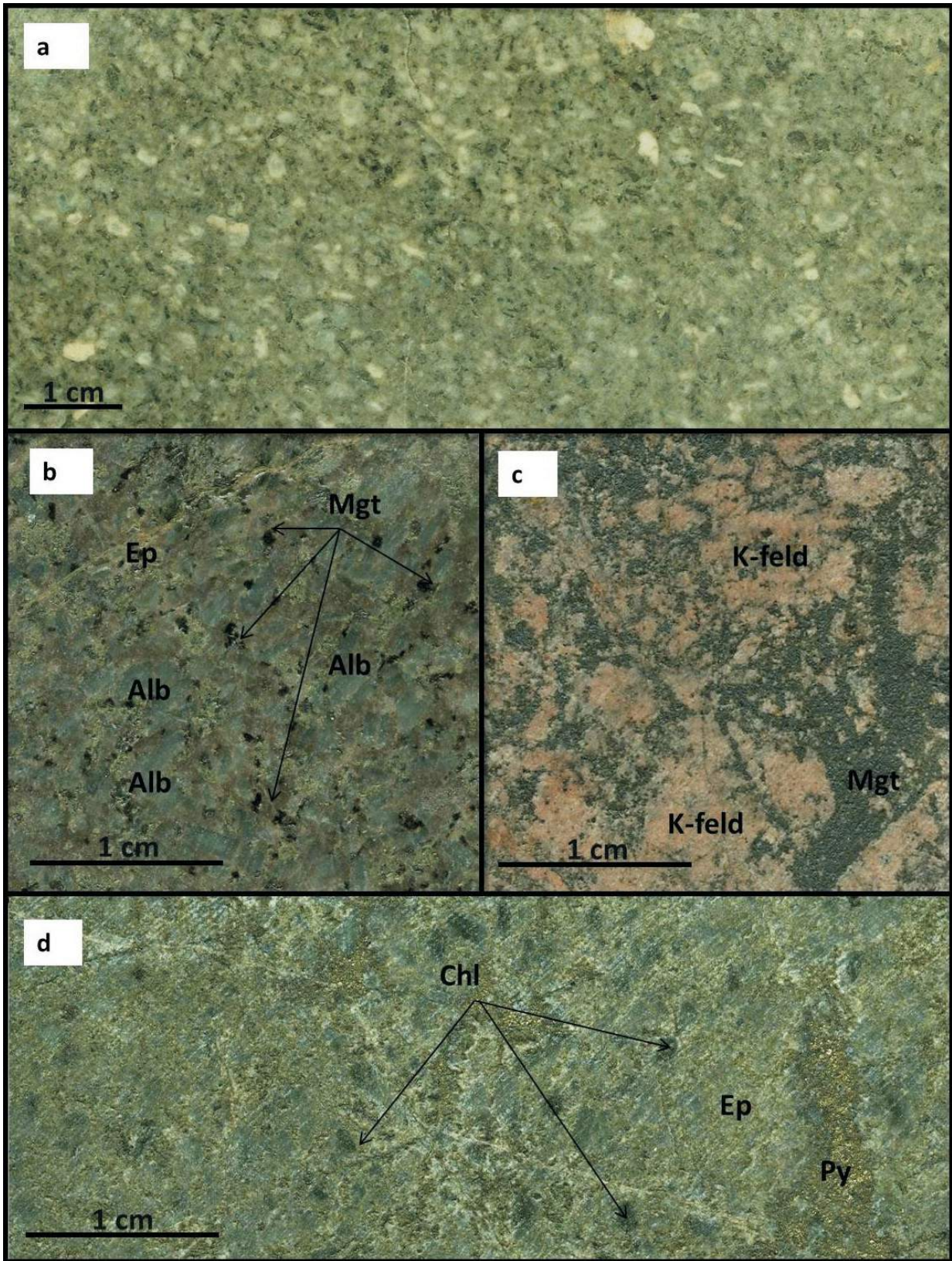


Figure 5. Photomicrographs of mineral assemblages of the Copper Mountain deposit, south-central British Columbia, showing **a)** diorite porphyry from Pit 2 (CM12P219_607m); **b)** sodic-calcic alteration assemblage of epidote+albite+magnetite from Alabama pit (CM12AB_19m); **c)** intense potassic alteration of K-feldspar matrix with disseminated magnetite from Pit 2 (CM12P221_413m); **d)** 'green alteration' assemblage of epidote+chlorite+calcite+pyrite from Pit 2 (CM12P223_352m). Core sample ID consists of hole number followed by depth. Abbreviations: Alb, albite; Chl, chlorite; Ep, epidote; K-feld, K-feldspar; Mgt, magnetite; Py, pyrite.

printing assemblages given its wide range of minerals and occurrence. Late-stage (post-mineralization) kaolinite alteration and sericite-chlorite-clay (SCC) alteration are structurally controlled and occur only locally. Texturally destructive kaolinite alteration consists of kaolinite+sericite+calcite+pyrite±epidote±chlorite±minor quartz; SCC alteration does not obliterate original textures and is typically pale green due to the presence of green clays (Stanley et al., 1992).

The main resistate minerals of interest at Copper Mountain, consisting of apatite, titanite, zircon, magnetite and possibly diopside, occur with the hostrock and associated alteration assemblages (Table 2).

Discussion

Alteration styles at Mount Polley, Mount Milligan and Copper Mountain, are similar, largely dominated by potassic assemblages. However, the size of the potassic zone, its mineralogy and the extent of the sodic-calcic and overprinting chlorite-epidote alterations vary from one deposit to the next, which in turn is expected to influence the occurrence and abundance of resistate minerals. At Mount Polley, the potassic alteration is more extensive than sodic-calcic alteration, with very strong orange, pervasive K-feldspar, biotite, actinolite and abundant disseminated magnetite overprinting the hostrock. A garnet-epidote+magnetite assemblage surrounds the potassic core. At Mount Milligan, potassic alteration is characterized by abundant K-feldspar±biotite±magnetite, which is surrounded by a epidote+chlorite+illite±pyrite assemblage. Garnet wasn't recognized but apatite and titanite occur with potassic alteration. Copper Mountain has widespread sodic (albite+diopside+epidote) and potassic (K-feldspar+biotite+magnetite) alterations. Some particular features of this deposit are pegmatitic K-feldspar+biotite veins and a

patchy 'green alteration' assemblage of epidote+chlorite+calcite±pyrite as well as an early-stage hornfels alteration. Apatite and titanite of the potassic alteration and diopside of the hornfels and sodic alterations are known resistate accessory minerals.

Therefore, it is evident that accessory minerals, such as apatite, titanite and magnetite, occurring with the potassic alteration and typically intergrown with Ti-bearing and sulphide phases, are the main candidates for PIMs studies in these deposits. Silicate minerals, such as diopside with sodic-calcic alteration and garnet with calcsilicate alteration, provide further PIMs potential. The occurrence and abundance of sodic-calcic alteration vary from one deposit to the next but this alteration commonly forms a larger zone outside the main mineralized zone, thus expanding the target volume of favourable PIMs hostrock. Additionally, alteration assemblages, such as chlorite-epidote-calcite, overprinting earlier potassic alteration, are common in the studied deposits. These lower-temperature assemblages can modify the texture and composition of the previously formed resistate minerals.

Future Work

Future work will include petrographic descriptions of the resistate minerals occurring in each alteration assemblage and hostrock type. This will be followed by more detailed analysis of selected resistate minerals in order to determine those diagnostic physical parameters and chemical compositions that will characterize indicator minerals in alkalic porphyry systems. A Mineral Liberation Analyzer (MLA), which is an automated scanning electron microscope, will be used for this purpose; the MLA provides information on mineral-species abundance, grain-size distribution, grain shape and composition. In addition to this, selected mineral separates will be characterized by cathodoluminescence

Table 2. Hostrocks, alteration assemblages, ore mineral assemblages and resistate minerals of the Mount Polley, Mount Milligan and Copper Mountain deposits, south-central British Columbia.

Deposit	Host rock	Alteration assemblages	Ore assemblages	Resistate minerals
Mount Polley	Diorite-monzonite	Actinolite, biotite, K-feldspar	Chalcopyrite, bornite, galena	Magnetite, apatite, titanite
		K-feldspar, magnetite		Magnetite, apatite, garnet
	Igneous breccia	Epidote, chlorite, calcite, pyrite		
Mount Milligan	Porphyritic monzonite	K-feldspar, biotite, magnetite	Chalcopyrite, bornite	Magnetite, apatite, titanite
		Epidote, chlorite, illite, pyrite		Magnetite, apatite, titanite
Copper Mountain	Diorite to monzonite	Biotite, K-feldspar	Chalcopyrite, bornite	Magnetite, apatite, titanite
		Albite, diopside, epidote, calcite		Apatite, titanite, zircon, diopside
	Syenite	Epidote, chlorite, calcite, pyrite		

and X-ray diffractometry, and subsequently will be analyzed for trace elements by laser-ablation inductively coupled plasma–mass spectrometry. Finally, whole-rock geochemistry of till samples may provide correlations between the abundance of indicator minerals and till composition and could be used as a proxy to reduce the number of heavy-mineral–concentrate samples required. By integrating these techniques, the most valid and cost-effective mechanism for characterizing PIMs can be established.

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