Porphyry Indicator Minerals (PIMs): Exploration for Concealed Deposits in South-Central British Columbia (NTS 092I/06, 093A/12, 093N/01, /14)

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Introduction

Resistate minerals, those robust accessory minerals that persist through weathering, have successfully been applied to kimberlite and diamond exploration (e.g., Griffin and Ryan, 1995; Averill, 2001). Although easy to collect in heavy mineral concentrates, these minerals have only rarely been used as exploration tools for other deposit types, including porphyry copper deposits (e.g., Force et al., 1984). The common occurrence of resistate minerals as alteration products in British Columbia porphyry copper deposits suggests that these porphyry indicator minerals (PIMs) could provide a key tool to the increase of exploration targeting success, especially in terrains covered by glacial till.

The Quesnel and Stikine terranes in south-central BC host Late Triassic–Early Jurassic magmatic arcs, which are highly prospective hosts for porphyry Cu (-Mo, Au) deposits. However, exploration success in this area has been limited due to thin, but extensive veneers of till and related glacial sediments, which cover much of the area (Ward et al., 2009), especially in the region between the Mount Milligan and Mount Polley porphyry deposits (Figure 1). Geophysical and geochemical surveys in this region (e.g., Sander Geophysics Limited, 2008; Jackaman et al., 2009; Kowalczyk, 2009) suggest that a broad correlation exists between the geochemical characteristics of these unconsolidated sediments and the underlying bedrock geology (Barnett and Williams, 2009). Therefore, an erosional mineralogical record of the bedrock, and more importantly of potentially mineralized porphyry copper deposits, likely exists in the glacial sediments, and this signature can be recognized by the resistate mineral population.

The purpose of this research project is to identify the occurrence, types, relative amounts and compositions of PIMs in selected porphyry deposits in order to elucidate important PIM signatures. The main questions are as follows:

What resistate minerals are key indicators for porphyry copper deposits in this region?

What are the characteristic features of these PIMs, particularly their physical appearance?

How extensive and intensive are PIM distribution patterns in surrounding sediments?

How can explorers most effectively and efficiently use PIMs in regional exploration targeting?

The key objectives of the project are therefore to

determine the occurrence and types of resistate minerals in various styles of alteration and mineralization in several central BC porphyry copper-gold deposits to establish a PIM signature;

determine the diagnostic physical parameters and chemical compositions of resistate minerals;

identify important indicator minerals and establish physical properties to distinguish those resistate minerals that are directly associated with porphyry copper-gold deposits; and

establish criteria for use of resistate minerals as an exploration tool in south-central BC.

This study presents a summary of field observations, sampling and preliminary results on contrasting characteristics of apatite crystals associated with mineralized and barren hostrocks at the Highland Valley porphyry copper district. These results suggest that apatite associated with porphyry copper mineralization has distinct physical and chemical properties, which can help to easily distinguish it from apatite associated with barren hostrocks.
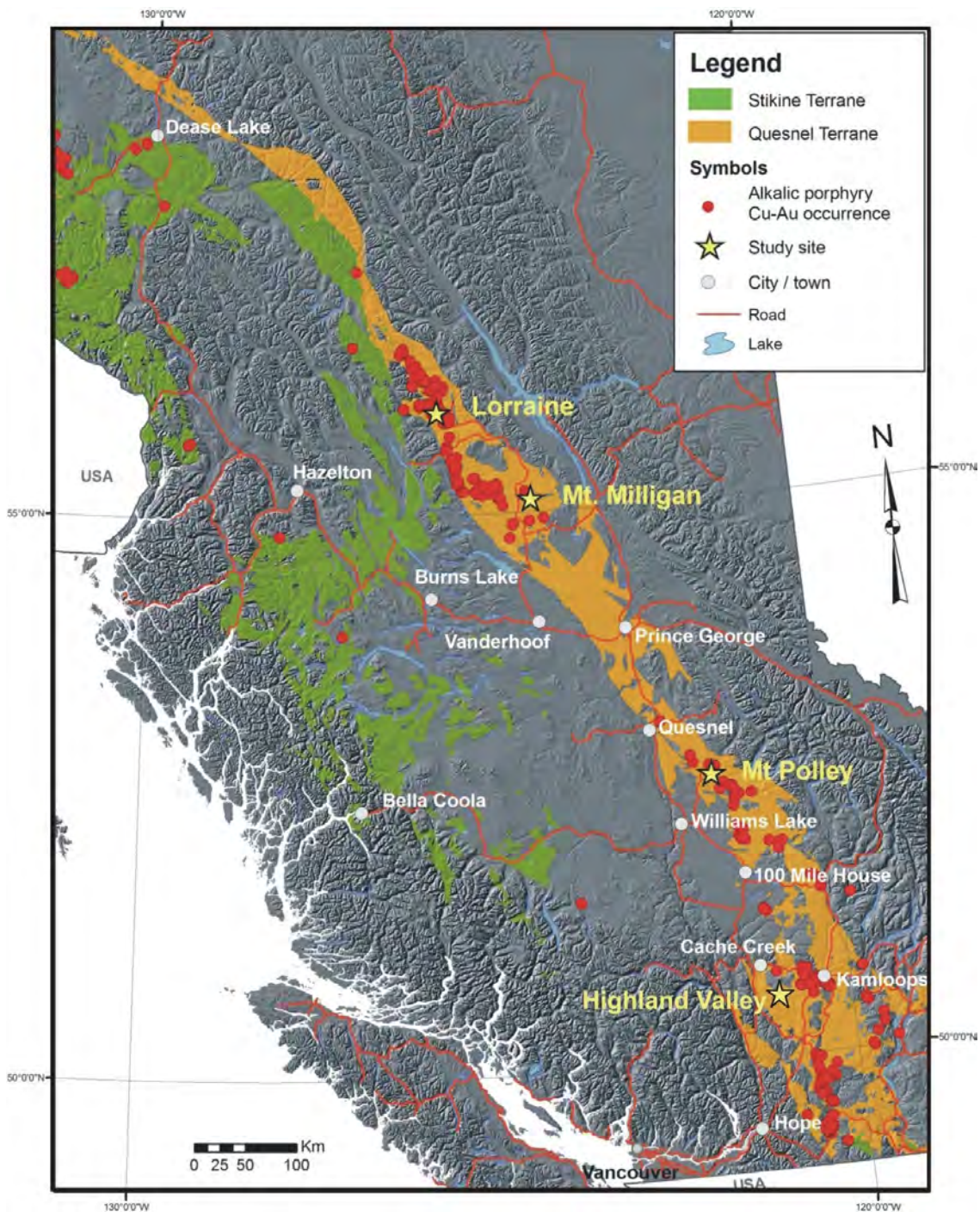
Figure 1. Digital elevation map showing outcrop distribution of Late Triassic and Early Jurassic Quesnel and Stikine terranes of south-central British Columbia (modified from Tosdal et al., 2008) and location of porphyry deposits selected for this study. Note the gap in occurrence of deposits in the area between the Mount Polley and Mount Milligan deposits.

Resistate Minerals in Porphyry Copper Deposits

Resistate minerals have long been known to occur in porphyry copper deposits, both in host intrusions and as hydrothermal alteration products (e.g., Schwartz, 1953; Gustafson and Hunt, 1975; Lang et al., 1995). Apatite, rutile, zircon, titanite, monazite and garnet are common resistate minerals associated with calcalkaline and alkaline porphyry deposits (Table 1). Tourmaline, dumortierite, andalusite, diaspore and quartz also commonly occur with calcalkaline porphyry deposits. Ore sulphide minerals are unstable and rarely preserved in surficial sediments, but supergene oxidation processes will convert these sulphide minerals into stable, insoluble minerals such as jarosite and turquoise, which can also be used as PIMs.

Table 1. Characteristics of resistate minerals occurring in British Columbia porphyry copper deposits.

Mineral	Density (g/cm^3)	Occurrence in porphry copper deposits	Characteristic features in porphyry deposits	South-central British Columbia example	References
Rutile	4.2	Occurs in potassic and phyllic zones as alteration product of biotite, ilmenite, titanomagnetite and titanite.	Red color due to high copper content; crystal length:width ratio increases outward from the deposit; grains proximal to the mineralized centre are larger and zoned; abundance and grain size follows the Cu grade; high concentration of V, Ta and Sc; Cr+V:Nb+Ta is high; V-Sb-W-rich rutile defines the Au-rich zone.	Mount Milligan, Babine Lake, Highland Valley	Williams and Cesbron, 1977; Desborough and Sharp, 1978; Czamanske et al., 1981; Harris, 1989; Nelson and Bellefontaine, 1996; Scott, 2005
Apatite	3.2	Occurs with early potassic alteration but records a history of dissolution and precipitation during subsequent alterations.	Fluoresce bright orange color in the ultraviolet; shows complicated history of corrosion and redeposition with a characteristic zoning (Liesegang rings); rings can often be detected 600–1000 m laterally away from the intrusion; commonly displays sulphur-rich cores abruptly changing to sulphur-poor rims; it is chlorine-rich.	Mount Polley, Galore Creek, Lorraine, Granisle	Carson and Jambor, 1974; Williams and Cesbron, 1977; Streck and Dilles, 1998; Tepper and Kuehner, 1999; Belousova et al., 2002; Kempe and Götze, 2002; Bath et al., 2006; Liaghat and Tosdal, 2008
Garnet	~3.9	Occurs in the periphery of porphyry deposits.	Displays zoning and change in composition; Ti-rich andradite commonly reported; hydrothermal titanian andradite can have as much TiSi as igneous varieties, but has zero or negative amounts of $TiMg[Fe^{3+}]_{-2}$	Mount Polley, Galore Creek, Lorraine	Watson, 1969; Russell et al., 1999; Nixon and Peatfield, 2003
Zircon	4.6	Commonly magmatic, occurring with the host intrusion but few studies report distinct hydrothermal zircon hosted in hydrothermal veins.	Rose zircon commonly reported; hydrothermal, spongy, inclusion-rich zircon may show complex internal textures in which secondary domains cut across primary growth zones; porphyry copper deposits are associated with intrusions with zircon having Ce(IV)/Ce(III)>300 and EuN/EuN*>0.4.	Mount Milligan, Mount Polley, Ajax	Mortensen et al., 1995; Nelson and Bellefontaine, 1996; Ballard et al., 2002; Hoskin, 2005; Pettke et al., 2005; Schaltegger, 2007
Monazite	~5.1	Commonly magmatic occurring with the host intrusion.	Hydrothermal monazite is characterized by its low ThO_2 content (0–1 wt. %) and is distinct from that of igneous monazite (3 to >5 wt. %).	Endako	Villeneuve et al., 2001; Schandl and Gorton, 2004
Titanite	~3.5	Commonly magmatic occurring with the host intrusion.	Blond titanite reported.	Mount Milligan, Mount Polley, Copper Mountain	Mortensen et al., 1995; Nelson and Bellefontaine, 1996
Tourmaline	~3	Commonly with transitional phyllic or breccia bodies.	Dravite is more common; associated with or without mineralization.	Megabuck Au-Cu prospect, Highland Valley	Panteleyev et al., 1996; Slack, 1996
Jarosite	~3	Supergene oxidation.	May occur with goetite and/or copper oxides.	Mount Milligan	

Resistate minerals can record salient features of the porphyry system from early magmatic (e.g., zircon) to late hydrothermal (e.g., apatite) and subsequent supergene oxidation stages. Thus, when formed or altered by hydrothermal fluids characteristic of the mineralizing porphyry environments, the physical properties of these minerals may change such that they display unique colour, size and shape characteristics, which can be used as a prospecting tool.

Early work on heavy accessory minerals in porphyry copper deposits mainly focused on the economic exploitation of these minerals (e.g., Czamanske et al., 1981). However, several studies noted the unique physical and chemical features of the resistate minerals associated with various stages of hydrothermal alteration in porphyry copper deposits (Table 1). More recently, chemical and physical properties of apatite and rutile were the subject of studies showing the overall evolution of the hydrothermal system (e.g., Streck and Dilles, 1998; Scott, 2005).

Apatite is a common accessory mineral occurring in various hostrocks and mineral deposits. Trace-element compositions of apatite have been used to recognize the hostrock and degree of fractionation, as well as the oxidation state of the host magma (Tepper and Kuehner, 1999; Belousova et al., 2002). Mariano (1988) and Kempe and Götze (2002) have shown that apatite from mineralization related to alkaline rocks exhibits blue and violet cathodoluminescence due to activation by trace quantities of rare earth element ions (Ce^{3+}, Eu^{2+}, Sm^{3+}, Dy^{3+} and Nd^{3+}), whereas those from P-rich granite show strong Mn^{2+}-activated yellow-greenish luminescence. Apatite from porphyry deposits is Cl-rich and Cl may act as a key component in transporting copper. Williams and Cesbron (1977) noted that apatite of porphyry copper origin displays a characteristic bright orange colour under ultraviolet (UV) light, and shows a complicated history of corrosion and redeposition with characteristic zoning (Liesegang rings). The rings can often be detected up to 600–1000 m laterally away from the intrusion. The composition of these textures is not well known but they may have recorded changes of the hydrothermal system through time and thus have the potential to provide clues to the productivity of the system. Furthermore, Streck and Dilles (1998) demonstrated that zoned apatites from the Yerington batholith, Nevada, have sulphur-rich cores which abruptly change to sulphur-poor rims, indicating that early sulphate-rich magma evolved to sulphate-poor magma via crystallization of anhydrite. Table 1 summarizes key characteristics of the common resistate minerals in porphyry copper deposits.

Geological Setting

Quesnel and Stikine terranes host most of BC's known porphyry copper deposits and are composed of Paleozoic and lower Mesozoic volcanic, sedimentary and plutonic rocks displaying both oceanic and arc affinities. The Late Triassic–Middle Jurassic porphyry deposits include both calcalkalic and alkalic classes, and show a full range of morphological and depth relationships (McMillan et al., 1995). The Highland Valley (NTS 092I/06), Mount Polley (NTS 093A/12), Mount Milligan (NTS 093N/01) and Lorraine (NTS 093N/14) deposits represent examples of the typical styles and assemblages of porphyry deposits in the Quesnel terrain and were therefore selected for this project (Figure 1).

The Highland Valley Cu-Mo district in southern BC is the largest cluster of porphyry deposits in the region and includes Valley, Lornex, Highmont, Alwin, Bethlehem and JA deposits hosted within the Upper Triassic calcalkaline Guichon Creek batholith (Casselman et al., 1995). This composite batholith ranges from diorite and quartz diorite at the border to younger granodiorite in the centre, which hosts the mineralization (Figure 2a). Styles and assemblages of alteration and mineralization vary from narrow structurally-controlled mineralized zones (e.g., Alwin) to pervasive stockwork-hosted mineralization (e.g., Valley); coarse secondary muscovite is a major alteration mineral in all deposits commonly accompanying sulphide mineralization (Figure 2b).

Figure 2. Examples of hostrock and alteration from the Alwin mine, Highland Valley, south-central British Columbia: **a)** sample of fresh Bethsaida granodiorite, the main hostrock to mineralization, with characteristic large, rounded quartz phenocrysts and biotite books; **b)** intense green mica alteration and associated chalcopyrite mineralization overprinting the Bethsaida granodiorite.

The alkalic Mount Polley Cu-Au deposit is hosted within Jurassic–Triassic diorite-monzonite intrusions and associated breccia bodies. Alteration-mineralization progresses outward from a higher temperature core of biotite to an intermediate actinolite zone and an outer zone of K-feldspar and albite (Fraser et al., 1995; Logan and Mihalynuk, 2005). Copper and gold values are closely correlated with high magnetite concentrations (Deyell and Tosdal, 2005).

The Middle Jurassic Mount Milligan deposits are hosted by porphyritic monzonite stocks and adjacent volcanic rocks of the Late Triassic Takla Group centred around three main intrusive stocks. The deposit displays a classic zoned alteration-mineralization pattern consisting of a bornite-rich core with potassic alteration surrounded by a pyrite-dominated sulphide halo with propylitic alteration (Sketchley et al., 1995; Jago and Tosdal, 2009).

Farthest to the north, the Lorraine alkalic Cu-Au porphyry deposit is hosted within the Duckling Creek Syenite Complex of the Late Triassic–Cretaceous Hogem batholith, which intrudes the Late Triassic Takla Group volcanic and sedimentary sequences (Nixon and Peatfield, 2003). Mineralization occurs in three zones along strike over a distance of approximately 1.5 km within a northwest-trending corridor dominated by syenitic rocks. Mineralization is characterized by finely disseminated Cu-Fe sulphide minerals in fine-grained K-feldspar biotite rock, biotite pyroxenite and syenitic rocks, and lacks features such as stockwork veining and breccia (Bath and Cooke, 2008). Chalcopyrite and bornite occur as blebs and semi-massive sulphide in pyroxenite (Bishop et al., 1995).

Materials and Methods

Sampling

Because their geology is well documented, Highland Valley, Mount Milligan and Lorraine deposits (Figure 1) were selected for sampling. Samples were selected from different alteration assemblages at different vertical levels to determine and characterize the occurrence of resistate minerals at various depths in a porphyry system. Samples were also collected from unmineralized hostrocks for direct comparison. Overall, 31 samples were collected from Highland Valley (Valley, Bethlehem and Alwin), and 12 samples were collected from Mount Milligan. A total of 13 samples representing Lorraine mineralization and various hostrocks were obtained from a previous study done by the Mineral Deposit Research Unit (MDRU) of the University of British Columbia (Bath and Cooke, 2008). Samples were also collected from Mount Polley Cu-Au and Endako Mo deposits for comparison. Furthermore, it is planned to obtain till and drainage sediments at various locations around at least one of the above study sites.

Methods

An integrated analytical technique is currently employed at MDRU to establish the most valid and cost effective mechanism for characterizing PIMs. Analytical work includes a petrographic study employing optical and cathodoluminescence (CL) microscopy and scanning electron microscopy (SEM) to characterize the abundance and physical properties of various resistate minerals, including shape, size, colour and luminescence. Selected grains are analyzed by electron microprobe for their trace-element composition to test whether there are key chemical features in the PIMs, which are unique to mineralized porphyry copper deposits. Resistate minerals have also been separated to different size fractions using conventional sieve and heavy liquid methods. These samples are currently being studied using a mineral liberation analyzer (MLA), which is an automated scanning electron microscope, to efficiently characterize the physical properties of the resistate minerals. The results of both the MLA and trace-element analysis by laser ablation inductively coupled plasma–mass spectrometry (LA-ICP-MS) will be made available in future presentations and publications.

Cathodoluminescence Microscopy

A Cambridge Image Technology Ltd. MK 4A model cold cathodoluminescence stage mounted on a petrographic microscope was used to study the internal textures of the apatite grains. The samples were irradiated in a vacuum chamber with an electron beam of approximately 15 kV and the current set at 350–500 µA.

Results

Petrographic observations indicate that apatite, zircon and, to a lesser extent, rutile and titanite are common resistate minerals in the studied deposits. Apatite is by far the most common resistate mineral occurring in a wide range of hostrocks and alteration assemblages. More critically, physical and chemical properties of apatite are significantly different in altered-mineralized rock relative to fresh hostrock largely based on observations from Highland Valley samples.

Apatite in fresh intrusive rocks commonly displays euhedral crystal shape and its hexagonal form is distinctive (Figure 3d). Although small apatite grains surrounded by quartz or feldspar are difficult to recognize under optical microscope, apatite was easily detected by its strong luminescence of yellow to yellow-green in fresh hostrock (Figures 2a, 3a). The yellow luminescence is attributed to excitation by Mn^{2+} (Mariano, 1988; Waychunas, 2002). Some of the apatite grains in fresh granodiorite display yellow-brown luminescence. No major internal structures were observed using either CL or SEM, although some grains show a distinctive narrow brownish luminescence zone near the crystal rim. Apatite in altered granodiorite at Highland Val-
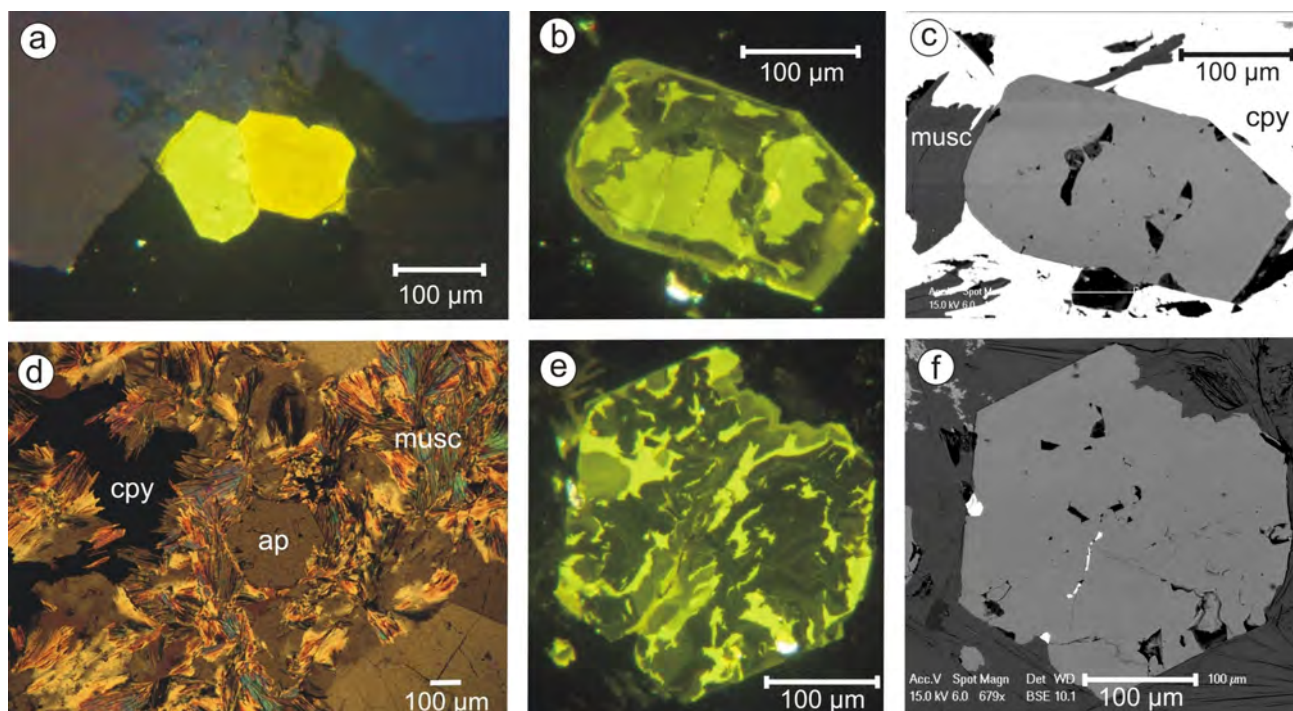
Figure 3. Photomicrographs showing contrasting characteristic features of apatite associated with fresh and altered Bethsaida granodiorite at Alwin mine, Highland Valley, south-central British Columbia: **a)** cathodoluminescence (CL) image showing two primary magmatic apatite grains hosted in fresh granodiorite with strong yellow (right) and yellow-pale green (left) luminescence with no obvious internal texture; **b)** CL image of apatite in altered granodiorite showing green-luminescent phase replaced by dark green- to grey-luminescent phase; **c)** scanning electron microscope (SEM) image of the apatite grain of Figure 3b showing no internal texture; **d)** crossed-polarized image of euhedral apatite (ap) crystal hosted in altered granodiorite with strong muscovite alteration (musc) and associated chalcopyrite (cpy) mineralization; **e)** CL image of the apatite grain of Figure 3d showing replacement of the green-luminescent apatite by a dark green- to grey-luminescent phase generating a 'messy' texture; **f)** SEM image of the apatite grain of Figure 3e showing no internal texture–the very bright phases at the rim and inside the apatite are chalcopyrite, which has formed within a micro-fracture that has an envelope of green to grey-luminescent apatite (see Figure 3e).

ley's Alwin mine looks very similar to that associated with unaltered granodiorite when examined using a polarizing microscope and SEM (Figures 3c, d, f). However, CL microscopy reveals that apatite associated with altered hostrocks displays a unique green luminescence, probably reflecting Fe^{2+} excitation, which is overprinted by a dark complex network and bodies of dark-green to grey-luminescent domains (Figure 3b), producing a characteristic 'messy' texture (Figure 3e). These relationships clearly demonstrate that a darker luminescent phase replaced a brighter, green-luminescent phase possibly contemporaneous with green muscovite alteration and associated copper mineralization.

Conclusions

Apatite is a ubiquitous accessory mineral which occurs in a wide range of hostrocks and commonly incorporates a wide range of trace elements. It is resistant to both late hydrothermal alteration and weathering, making it a robust, easy to collect recorder of mineralization-related alteration. Altered apatite displays yellow-green luminescence probably due to excitation by incorporation of low amounts of Fe^{2+}. Strongly altered apatite shows dark-green to grey luminescence, probably due to the loss of Mn^{2+}, producing a complex texture with remnants of green-luminescent apatite. Preliminary microprobe data suggest that apatite in altered hostrock has lost several trace components such as Mn^{2+}, Cl and S. These results provide the first step towards a better understanding and, ultimately, the use of resistate minerals as indicators for porphyry copper exploration.

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