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

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Introduction

The occurrence of resistate minerals such as apatite, titanite, garnet and rutile in the surficial environment proximal to mineralized and altered portions of British Columbia's alkalic porphyry copper deposits suggests that these minerals can be utilized as exploration tools, especially in terrains covered by glacial till (Bouzari et al., 2011). Before such minerals can be utilized for exploration, the physical and chemical properties of these porphyry indicator minerals (PIMs) must first be established. This paper will characterize the occurrence, type, relative amount and composition of selected PIMs at the Copper Mountain, Mount Polley and Mount Milligan porphyry deposits (Figure 1), in order to elucidate important PIM signatures and then evaluate these signatures in proximal tills, stream sediments and heavy mineral concentrates. This paper presents the results of a project that evaluates PIMs that are directly associated with alkalic porphyry deposits, and builds upon information previously presented (Celis et al., 2013).

A detailed petrographic study of 60 samples representing various hostrocks, and alteration and mineralization assemblages from the Copper Mountain, Mount Polley and Mount Milligan deposits, was undertaken using transmitted and reflected light microscopy, as well as scanning electron microscopy (SEM). In addition, heavy mineral separates derived from bedrock (16 samples) and from till sediments (14 samples), covering the Mount Polley and Mount Milligan deposits, were collected and are currently under investigation. This paper summarizes the results of the petrographic study, characterizing PIMs occurring within the porphyry deposit.

Resistate Minerals in Alkalic Porphyry Deposits

Resistate minerals occur as rock-forming minerals in alkalic intrusions and are modified or precipitated during the hydrothermal processes that result in the formation of porphyry copper deposits. The occurrence and some key characteristics of resistate minerals such as apatite, magnetite, garnet, rutile and zircon have been previously described for porphyry deposits (e.g., Bouzari et al., 2011). Primary magmatic apatite in hostrock and in early potassic alteration can record a history of dissolution and precipitation during subsequent hydrothermal alteration. Magnetite can form a resistate phase when aggregated with rutile, titanite and quartz. Magnetite with a uniform pinkish-grey colour in reflected light (RL) indicates a high Ti content and probable magmatic origin. Rims of hematite and titanite around magnetite indicate an increase in the oxidation state of the latest crystallizing melt. Garnet can occur at the peripheries of porphyry deposits and can display mineral zoning, dissolution and changes in chemical composition in response to hydrothermal evolution. In potassically altered rocks, rutile occurs as relicts of altered biotite, ilmenite, titanomagnetite and amphibole. Titanite is commonly magmatic, occurring within the host intrusion, and displays a characteristic blonde colour in transmitted light (TL; Bouzari et al., 2011).

Magnetite and titanomagnetite are common oxide phases in alkalic plutonic rocks. During the magmatic processes, the occurrence and composition of the Fe-Ti oxides is determined by the composition of the melt from which they crystallized and also by re-equilibrium reactions between the oxides and the silicates in the hostrock.

Hydrothermal fluids may partially or totally modify the original physical properties of these resistate minerals, which can ultimately result in the precipitation of a new hydrothermal mineral phase. For example, small (<100 μm), euhedral, colourless and uniform-textured magmatic apatite crystals are commonly regrown and modified to show subhedral to anhedral habits, and display a distinctive cloudy, highly porous texture. Some of the processes and reactions responsible for the generation of resistate minerals by magmatic and hydrothermal reactions are listed below (Table 1).

Analytical Methods

Petrography and SEM

Petrographic analysis of 60 thin sections from Mount Polley, Mount Milligan and Copper Mountain was performed using TL and RL microscopy, as well as scanning electron microscopy (SEM). Mineralogical and textural characteristics of different alteration assemblages were documented first. This was followed by the characterization of resistate minerals occurring within the fresh hostrock, as well as within representative samples of each
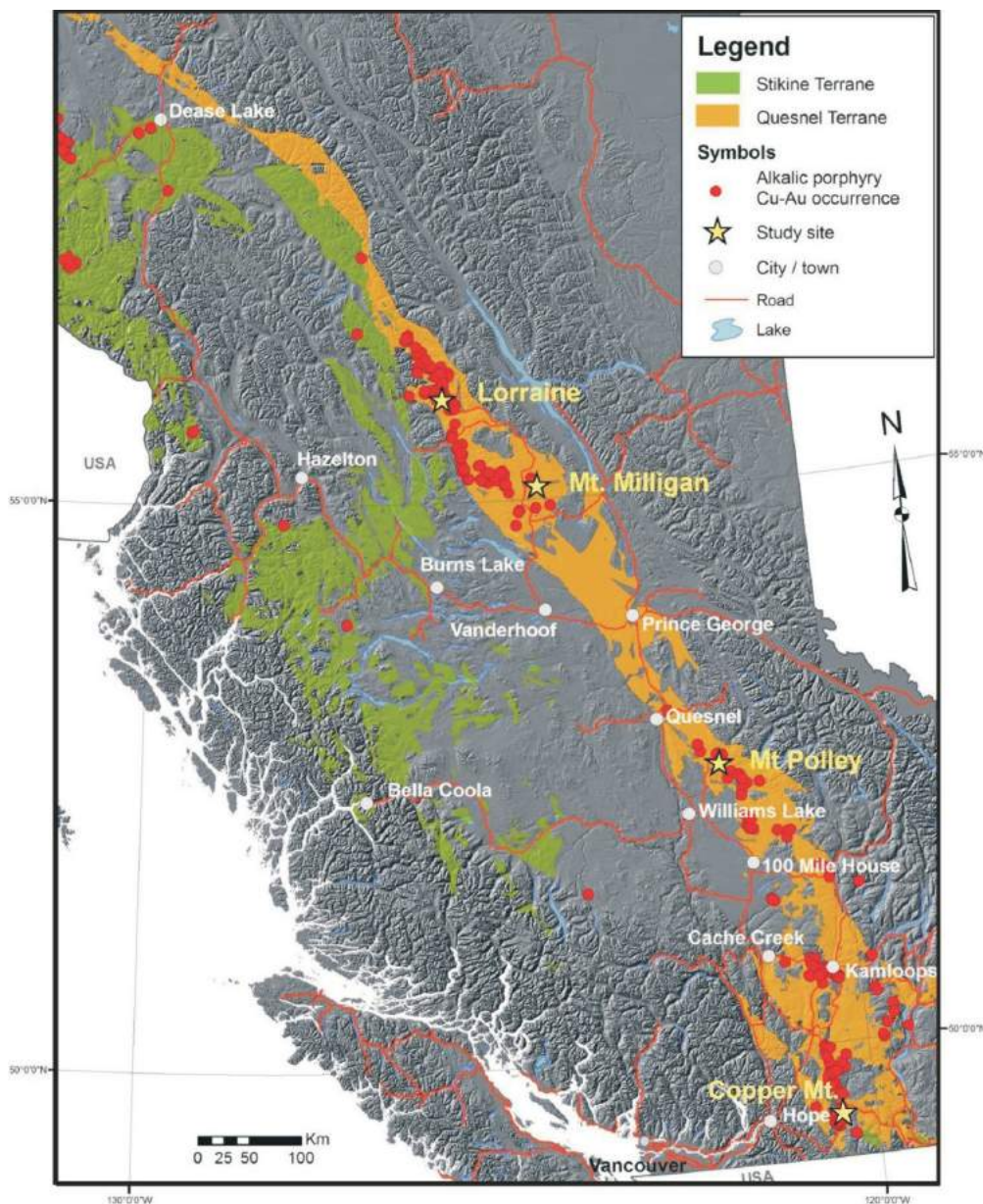

Figure 1. Digital elevation map showing Triassic and Early Jurassic Quesnel and Stikine terranes of south-central British Columbia and location of selected deposits (modified from Tosdal et al., 2008). Figure compiled using digital elevation data from GeoBase® (2004) with postprocessing by K. Shimamura (Geological Survey of Canada); MINFILE database (porphyry occurrences; BC Geological Survey, 2013); and the tectonic assemblage map of the Vancouver area (Journeay et al., 2000).

Table 1. Summary of magmatic and hydrothermal reactions that generate resistate minerals.

An increase in the oxidation state of the magma during cooling results in the formation of ilmenite and magnetite as exsolution lamellae after titanomagnetite (Lindsley 1991). $6Fe_2TiO_4 + O_2 = 6FeTiO_3 + 2Fe_3O_4$ (titanomagnetite = ilmenite + magnetite)
During K-feldspar alteration, interaction between titanomagnetite/ilmenite and sulphur-rich fluids form rutile and sulphide phases (Lindsley 1991). $2(H_2S, Cu^{2+}) + 2FeTiO_3/Fe_2TiO_4 = FeS_2/CuFeS_2 + TiO_2$ (fluid + ilmenite/titanomagnetite = pyrite/chalcopyrite +rutile)
Hydrothermal fluids interacting with Ti-bearing mafic phenocrysts form rutile and sulphides (Lindsley 1991). $2(H_2S, Cu^{2+}) + 2K(Fe,Ti)_3AlSi_3O_{10}(OH)_2 = CuFeS_2 + (Fe,Al)_3(Si,Al)_4O_{10}(OH)_2 +$ $K(Al,Fe)_2(SiAl)_4O_{10}(OH)_2nH_2O + TiO_2$ (fluid + Ti-biotite = chalcopyrite + chlorite + sericite + rutile)
Titanite is a common Ti-bearing resistate mineral in alkalic hostrocks. During early magmatic processes, titanite can form after augite and ilmenite (Xirouchakis and Lindsley 1998). $3CaFeSi_2O_6 + 3FeTiO_3 = 3CaTiSiO_5 + Fe_3O_4 + 9SiO_2$ (augite + ilmenite = titanite + magnetite + quartz)
A similar reaction accompanying K-feldspar alteration forms titanite and sulphide phases (Lindsley, 1991). $3CaFeSi_2O_6 + 3FeTiO_3 + (H_2S,Cu) = 3CaTiSiO_5 + 6FeS_2/CuFeS_2 + 9SiO_2$ (augite + ilmenite + fluid = titanite + pyrite/chalcopyrite + quartz)
Hydrothermal fluids interacting with carbonate mineral phases result in the formation of mineral phases such as andraditic garnet (Dasgupta and Supratim, 2005). $3SiO_2 + 3CaCO_3 + Ca_2Al_2(Fe_3+Al)(SiO_4)(Si_2O_7)O(OH) = Ca_3Fe_2+2(SiO_4)_3 + 3CO_2$ (quartz + calcite + epidote = andradite)

alteration assemblage. The PIMs were then characterized within each alteration according to their paragenesis and physical properties such as colour, habit, texture and grain size.

Geology and Alteration

Copper Mountain

The Copper Mountain deposit is centred on two Late Triassic intrusions, composed predominantly of pyroxene diorite to monzonite and syenite, and hosted within the Triassic Nicola volcanic sequence (Stanley et al., 1992). Alteration assemblages comprise an early stage of hornfels alteration, overprinted by sodic and potassic alteration.

Potassic alteration is characterized by pink K-feldspar replacing plagioclase, locally crosscuts zones of pre-existing sodic-calcic alteration, and is widely distributed throughout the deposit (Stanley et al., 1992). Magnetite-chalcopyrite and titanite-chalcopyrite assemblages are common within the potassic alteration zone. Magnetite occurs as coarse subhedral to anhedral grains up to 500 μm. Titanite grains display characteristic wedge-shaped crystal habit and show a distinctive brownish colour in TL.

Sodic alteration is characterized by abundant albite that is confined to the central portion of the deposit and typically expressed as bleached, pale greyish-green or mottled white alteration of the hostrock (Stanley et al., 1992). Augite and titanite are common within sodic alteration. Rhombohedral titanite grains up to 300 μm display characteristic colourless to pale brown colour. Partial replacement of mafic phenocrysts and titanite grains by small anhedral rutile grains is also common.

A dark to light green chlorite+actinolite+epidote± pyrite± calcite alteration assemblage typically occurs at the periphery of the deposit, but also may occur in the central part along with potassic alteration (Stanley et al., 1992). Magnetite and titanite grains within this alteration zone are less abundant and smaller in size. A magnetite-titanite assemblage replacing mafic phenocrysts is typical within this alteration.

Apatite is ubiquitously distributed and occurs as coarse (500 μm) subhedral to anhedral colourless grains with a cloudy appearance and highly porous texture. Small (<10 μm) monazite inclusions may occur.

Mount Polley

The Mount Polley deposit is centred within and around several diorite to monzonite intrusions of Upper Triassic to Lower Jurassic age hosted in the Triassic Nicola volcanic sequence (Fraser et al., 1995). Alteration at Mount Polley consists of three concentrically zoned alteration assemblages (Fraser et al., 1995): a potassic core surrounded by a constrained garnet-epidote zone and an outer propylitic zone. The potassic core has been further divided into three distinct zones: biotite (100 m wide), actinolite (250 m wide), and K-feldspar–albite zone (1 km wide; Hodgson et al., 1976; Bailey and Hodgson, 1979). Magnetite is the dominant Fe-oxide mineral in the potassic alteration zone and commonly occurs as vein material and disseminated grains. Rhombohedral- to wedge-shaped titanite grains are commonly associated with chalcopyrite, whereas less abundant small (<50 μm) anhedral rutile replaces biotite phenocrysts. Garnet occurs as very coarse (>1000 μm) pale yellow grains in the garnet-epidote zone. The outer 'green alteration' propylitic zone includes a mineral assemblage of albite, epidote, chlorite with calcite veins and variable amounts of disseminated pyrite. Replacement of mafic phenocrysts by epidote±titanite is common. Titanite typically occurs as rhombohedral- to wedge-shaped grains with a distinctive pale brownish colour in TL. Apatite is ubiquitously distributed and occurs as coarse (500 μm) subhedral to anhedral colourless grains with a cloudy highly porous texture.

Mount Milligan

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

In potassic alteration, magnetite typically occurs as coarse (200–400 μm) subhedral grains with homogeneous to lamellar texture. Mafic phenocrysts replaced by magnetite-pyrite are common. Generally, magnetite is less common in Mount Milligan relative to Mt. Polley and Copper Mountain.

Small (<50 μm) anhedral to acicular rutile crystals commonly occur within magnetite, titanite and mafic phenocrysts. Titanite at Mount Milligan is rare and in TL displays a characteristic pale brown colour and anhedral to wedge-shaped habits.

Apatite is ubiquitously distributed and occurs as coarse (500 μm) subhedral to anhedral colourless grains with cloudy highly porous texture.

Characterization of Selected PIMs

Mineral paragenesis and their physical properties such as habit, colour, texture and size are the key parameters used to characterize PIMs in alkalic porphyry systems. PIMs are divisible into four types: 1) those that crystallized from magma (magmatic); 2) those magmatic minerals that have been physically or chemically modified by hydrothermal fluids (altered); 3) those that exsolved from previously crystallized minerals (exsolved); and, 4) those that precipitated directly from a hydrothermal fluid (hydrothermal). Some examples of magmatic PIMs are rock-forming minerals such as olivine, pyroxenes, amphiboles, K-feldspar, plagioclase and opaque minerals such as magnetite and titanite. Altered PIMs are most typically magmatic minerals that have undergone compositional change because of hydrothermal fluid interactions. Variation in the chemistry of apatite or the conversion of magnetite to hematite represent two examples of hydrothermally altered PIMs. Exsolved PIMs are those forming as lamellae and in exsolution textures such as in many Fe-Ti oxides. Hydrothermal PIMs are those grains newly precipitated either as flooding, disseminations or veins, and include secondary K-feldspar, secondary biotite, chlorite, actinolite and magnetite.

Magnetite

Magmatic magnetite typically displays euhedral cubic grains, from 100 to 300 μm in size with abundant ilmenite lamellar textures at all three studied deposits (Figure 2a, b). In potassically altered rocks at Mount Polley and Copper Mountain, hydrothermal magnetite grains are commonly coarse (>500 μm), show subhedral to anhedral habit with uniform texture and are distributed within the K-feldspar groundmass. Magnetite occurrences can be massive to vein type with common magnetite-chalcopyrite assemblages (Figure 2c, d). In the propylitic zone at all three deposits magnetite is less abundant and tends to preserve its subhedral to anhedral habit and homogeneous texture, but its size tends to decrease (<200 μm), and massive to vein-type occurrences are absent. Magnetite-pyrite replacing mafic phenocrysts (Figure 2e) is common within propylitic-altered rocks of Mount Milligan. Some diagnostic characteristics of magnetite are: euhedral to subhedral cubic habit, light grey colour in RL with lamellar texture in least-altered hostrocks (magmatic magnetite), and subhedral to vein habit, pinkish-grey colour in RL and uniform texture in potassically altered rocks (altered magnetite).
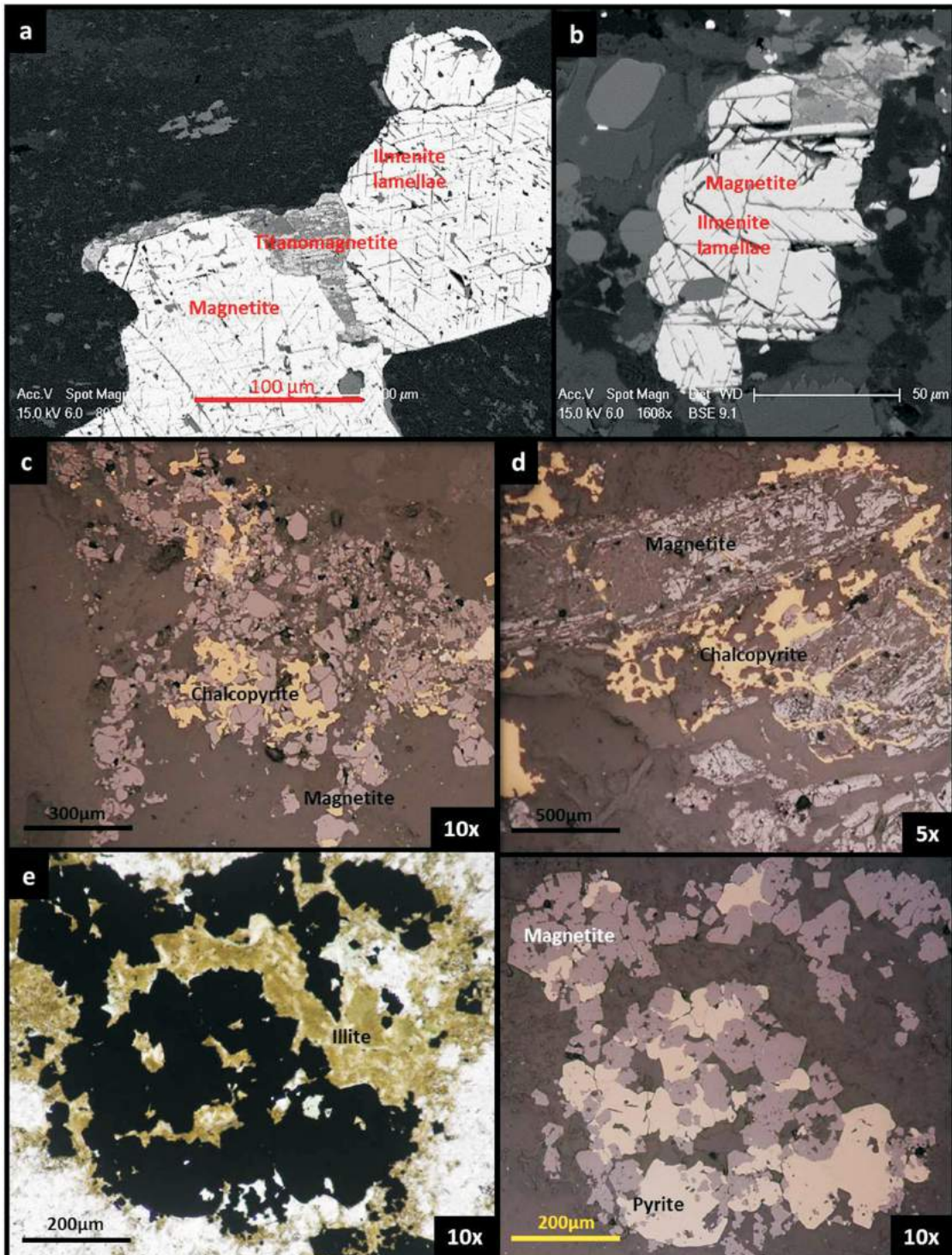
Figure 2. Photomicrographs of magnetite, south-central British Columbia: **a)** scanning electron microscope (SEM) backscattered image of euhedral magnetite, 400 μm grain size, with abundant ilmenite lamellae and exsolution texture of least-altered rocks, Copper Mountain, sample from south access to mine road (UTM 681500N, 5468302E, NAD 83, Zone 19; CMT-13); **b)** SEM backscattered image of magnetite, subhedral habit, 100 μm size, with abundant ilmenite lamellae and exsolution texture, in least-altered rocks, Mount Polley, sample from road to the tailings (UTM 5822071N, 592687E; P-10); **c)** magnetite with homogeneous texture, subhedral habit, 100–200 μm size, containing chalcopyrite bodies in K-feldspar alteration, Mount Polley, sample from Springer pit (P-1); **d)** magnetite with homogeneous texture, subhedral to anhedral habit, 100 μm size, intergrown by chalcopyrite in K-feldspar alteration, Copper Mountain, sample from Alabama pit (CM12AB12_65.5m); **e)** magnetite with homogeneous to lamellar texture, subhedral habit, 200 μm size, intergrown with pyrite replacing a mafic phenocryst in propylitic altered rocks containing green clay illite, Mount Milligan, sample from 66 zone (07992_81.5m).

Titanite

Titanite is the most abundant titanium-bearing mineral in the studied deposits. Copper Mountain and Mount Polley contain up to 3% titanite, and Mount Milligan contains less than 1%.

Magmatic titanite grains have typical rhombohedral habit, uniform texture and are colourless to pale brownish colour in TL with sizes ranging from 100 to 300 μm. Typical augite-titanite assemblages can be found within sodic alteration at Copper Mountain (Figure 3a). Hydrothermal titanite typically occurs within the potassic-altered rocks at all three deposits. These grains are rhombohedral, wedge shaped to anhedral in habit, with serrated edges and display a more brownish colour in TL than magmatic titanite. Typical occurrences of hydrothermal titanite at Copper Mountain are titanite-chalcopyrite clusters (Figure 3b) and rutile replacements (Figure 3c)

Titanite within propylitic-altered rocks tends to have smaller grain size (100 μm) and lower modal abundance (1%). Titanite with a wedge-shaped crystal habit, together with chlorite and epidote is common. In addition, a titanite-magnetite assemblage (Figure 3d) replacing mafic phenocrysts occurs locally.

Diagnostic characteristics of magmatic titanite include rhombohedral- to wedge-shaped habit, colourless to pale brownish colour and high relief in TL, dark grey colour in RL and uniform texture.

Apatite

Apatite is a rock-forming accessory mineral that crystallizes late from residual magma, occupying interstitial spaces within the groundmass of intrusive hostrocks or adjacent to mafic phenocrysts. Its diagnostic characteristics include euhedral prismatic colourless crystals of small size (<100 μm) and uniform texture (Figure 4a). Hydrothermal apatite is typically coarse (300–1000 μm), colourless, subhedral to anhedral habit, and displays a characteristic cloudy, highly porous texture (Figure 4b, c). Hydrothermal apatite is ubiquitously distributed in all studied deposits and its relative abundance is significantly higher (2%) than magmatic apatite (<1%).

Garnet

Garnet occurs exclusively within a transitional garnet-epidote alteration zone between the potassic core and the outer propylitic zone at the Mount Polley deposit. Garnet typically occurs as very coarse (>1000 μm) subhedral to anhedral grains of yellow colour in TL (Figure 4c). Massive garnet veins (Figure 4e) and epidote±garnet assemblages suggest a hydrothermal origin. The diagnostic features of garnet are its brown to honey-brown colour and high relief

in TL, isotropy under cross-polarized light (XPL), subhedral cubic to vein habits and fractured texture.

Table 2 summarizes characteristics of the selected porphyry indicator minerals. Classification is on the basis of their origin and characteristic physical properties within least-altered and altered rocks from alkalic porphyry deposits.

Discussion

Detailed petrographic characterization of apatite, garnet, magnetite and titanite from the Copper Mountain, Mount Polley and Mount Milligan deposits, confirmed high abundances of magnetite (10%) and titanite (>4%) in potassically altered alkalic plutonic rocks. Also, exsolution lamellae and replacement textures are consistently found in euhedral to subhedral magmatic magnetite grains. These mineralogical features represent a late magmatic stage of a porphyry-type intrusion as Fe-Ti oxides re-equilibrated during cooling.

Subsequently, rhombohedral titanite is the dominant titanium-bearing mineral in the studied deposits and mainly originates from the augite-titanomagnetite (oxide-silicate) equilibrium during cooling.

As hydrothermal fluid-rock interaction developed within the studied alkalic porphyry systems, a new precipitation of magnetite and titanite took place. Hydrothermal magnetite typically occurs as disseminated medium to coarse grains and local veins. Magnetite together with chalcopyrite± bornite is a common assemblage in potassically altered rocks, whereas magnetite±pyrite replacement of augite and other mafic minerals is characteristic in propylitic alteration. Generally, magnetite distribution and grain size tend to decrease from the centre (1000 μm) to the periphery (<100 μm) of each deposit.

Hydrothermal titanite precipitated together with chalcopyrite±bornite and displays subhedral to anhedral habit with serrated edges and a characteristic brown colour in TL. Also, titanite interacting with CO_2-rich fluids may have resulted in precipitation of very small (<50 μm) subhedral to acicular rutile grains. The very small size of rutile makes it an impractical PIM due to its low preservation and recovery potential in porphyry-derived sediments. Generally, titanite and rutile abundance tends to be higher in the potassic centre of a deposit and gradually decreases outward to the propylitic zone.

Garnet occurs exclusively in a transitional garnet+epidote alteration zone between the potassic and propylitic alteration zones at the Mount Polley deposit as very coarse (>1000 μm) anhedral grains to veins. Its coarse-grained to massive occurrence, honey-brown colour, high relief in
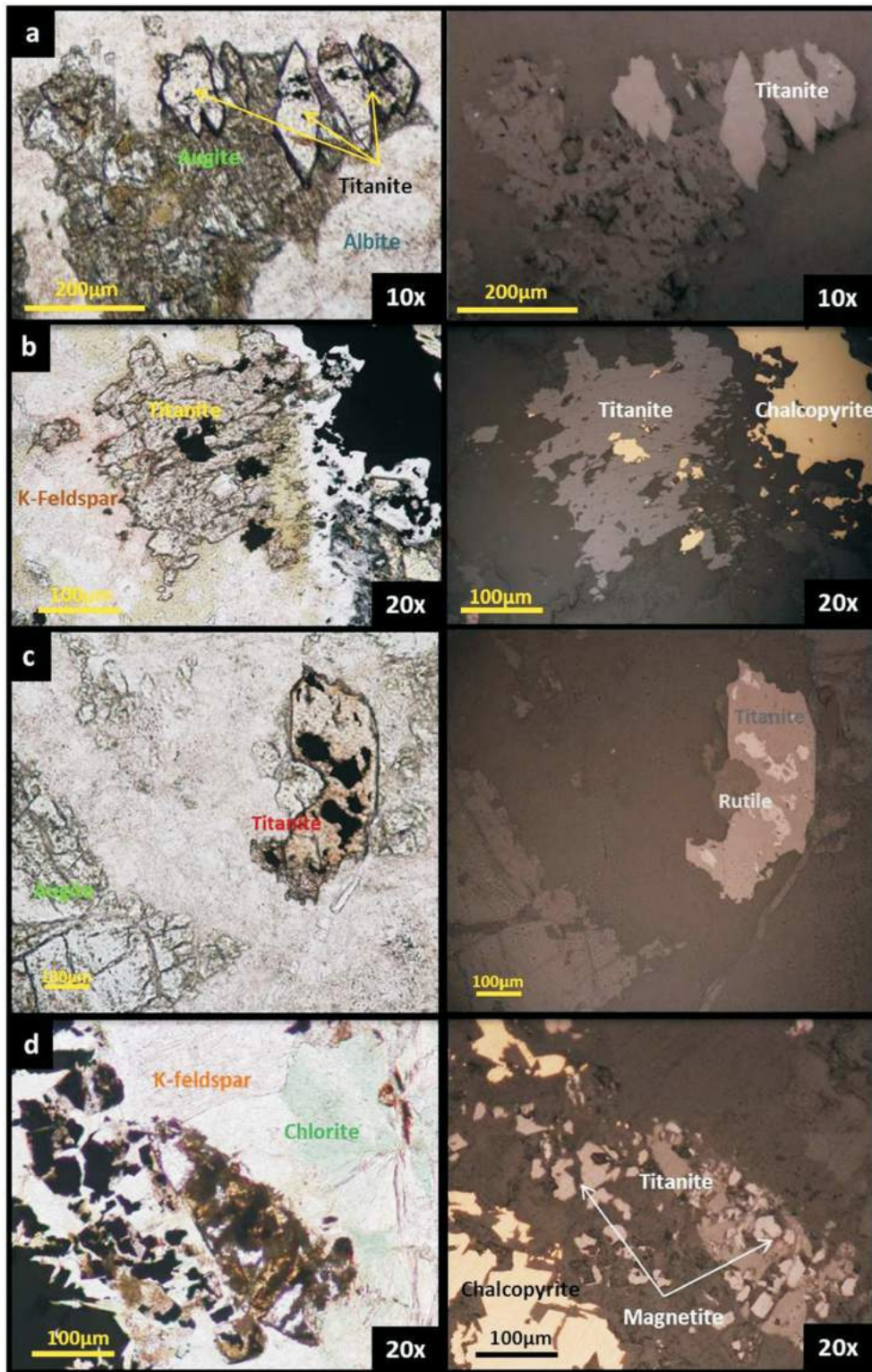
Figure 3. Photomicrographs of titanite taken using both transmitted light (left) and reflected light (right): **a)** titanite, rhombohedral habit, colourless to pale brown, 200 μm size grains in association with larger augite phenocryst in sodic alteration zone, Copper Mountain, sample from Pit 2 (CM12AB19_181.5m); **b)** titanite, anhedral habit, colourless to pale brown, 100–200 μm size grains with chalcopyrite inclusion in K-feldspar alteration zone, Copper Mountain, sample from Pit 2 (CM12P221_241m); **c)** titanite, subhedral to anhedral habit, pale brownish, 300 μm size grains with rutile exsolution texture in K-feldspar alteration, Copper Mountain, sample from Pit 2 (CM12P221_144.5m); and **d)** titanite, subhedral habit, brownish, 100 μm size grains in association with small subhedral magnetite grains in propylitic alteration zone, Copper Mountain, sample from Virginia pit (CMT-1).
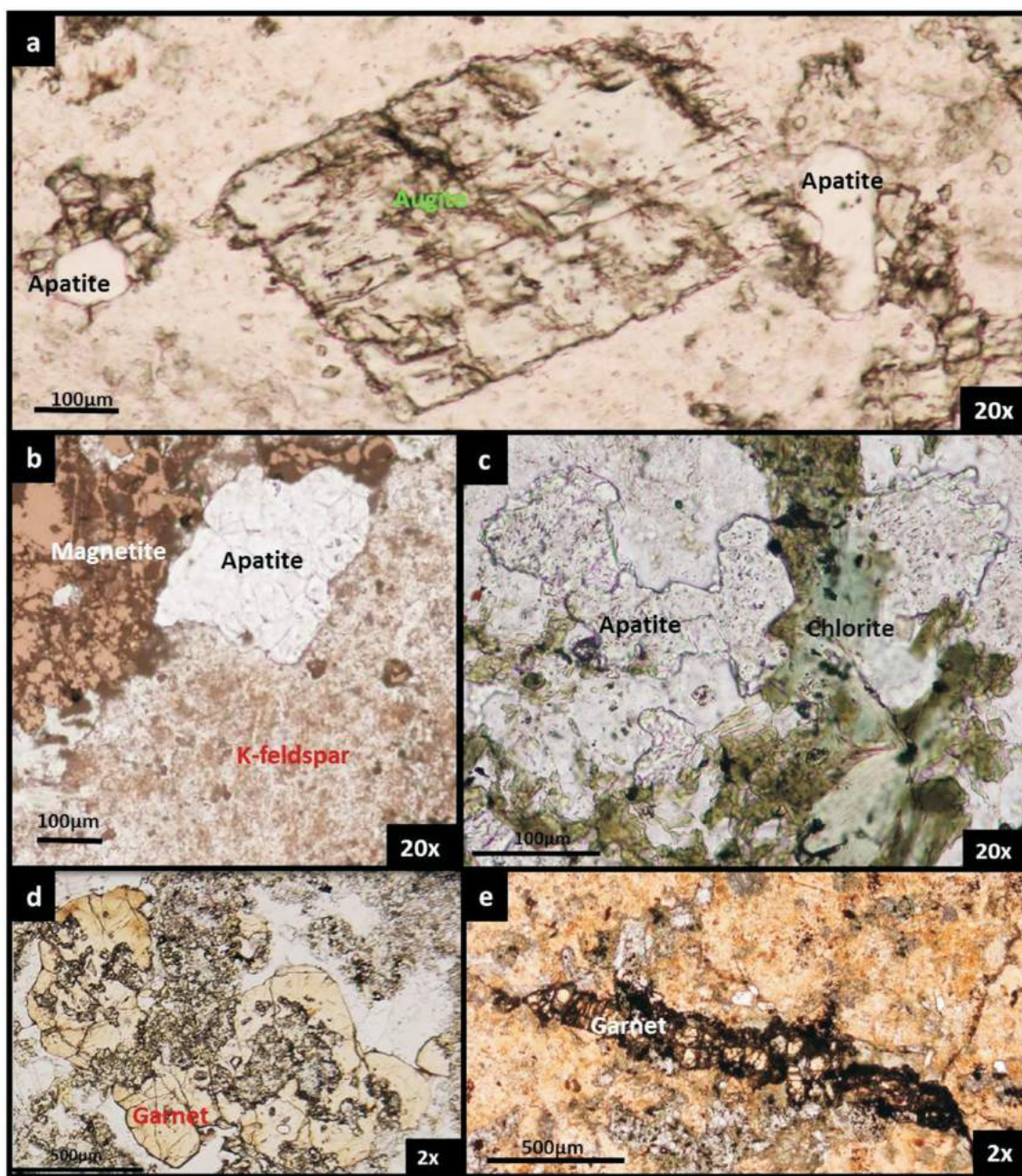
Figure 4. Photomicrographs of apatite and garnet, south-central British Columbia: **a)** apatite, colourless, uniform texture, euhedral prismatic habit, 100 μm size crystals intergrown with large augite phenocrysts in sodic alteration zone, Copper Mountain, sample from Pit 2 (CMT-6); **b)** apatite, colourless, cloudy, highly porous texture, anhedral habit, 400 μm size crystal adjacent to anhedral magnetite grains in K-feldspar alteration, Mount Polley, sample from Springer pit (Polley-1); **c)** apatite, colourless, cloudy, highly porous texture, subhedral habit, 200 μm size crystals adjacent to chlorite after biotite phenocrysts in propylitic alteration, Mount Milligan, sample from 66 zone (07992_81.5m); **d)** garnet, pale yellow, subhedral to anhedral habit, very coarse grain size (1500 μm), intergrown with epidote in garnet-epidote alteration zone, Mount Polley, sample from Springer pit (Polley-4); and **e)** garnet, pale yellow, very coarse grain size (1500 μm) within a vein in the garnet-epidote alteration zone, Mount Polley, sample from Whight pit (Polley-9).

TL, and its isotropic property under XPL, are diagnostic characteristics of garnet.

Apatite is ubiquitously distributed throughout all three studied deposits. Its common, very coarse (500–1000 μm), anhedral grains with a characteristically cloudy appearance and highly porous texture, demonstrate magmatic origin that has been modified by hydrothermal alteration. Magmatic apatite is less common and occurs as small (100 μm) euhedral prismatic grains that occupy interstitial spaces of the silicate matrix, as well as spaces adjacent to mafic phenocrysts.

Table 2. Classification and characterization of porphyry indicator minerals (PIMs) within alkalic porphyry deposits, south-central British Columbia.

PIM	Origin	Shape	Physical properties				Common paragenesis
			Colour in TL	Colour in RL	Texture	Size	
Apatite	Magmatic	Euhedral prismatic	Colourless		Clean	<100 μm	Interstitial spaces, adjacent to mafic minerals
	Hydrothermal	Subhedral to anhedral, prismatic	Colourless		Cloudy; high porosity	>300 μm	Adjacent to mafic minerals, magnetite and sulphides
Garnet	Hydrothermal	Anhedral to vein shaped	Pale yellow		Cloudy; fractured	>1000 μm	Epidote-garnet assemblages
Magnetite	Magmatic	Euhedral cubic		Grey	Ilmenite lamellae ±titanomagnetite exsolution	100–300 μm	Adjacent to mafic minerals
	Altered	Subhedral cubic		Grey	Homogeneous ±ilmenite lamellae; rims of titanite/hematite	100–500 μm	Intergrain exchange with chalcopyrite±pyrite
	Hydrothermal	Anhedral to vein shaped		Grey	Homogeneous	>300 μm	Intergrain exchange with chalcopyrite±pyrite±rutile
Titanite	Magmatic	Rhombohedral	Colourless to pale brown	Dark grey	Homogeneous	100–300 μm	Interstitial spaces, titanite-augite assemblage
	Hydrothermal	Rhombohedral to wedge shaped, anhedral with serrated edges	Pale brown to brown	Dark grey	Homogeneous to rutile exsolution	100–300 μm	Intergrain exchange with chalcopyrite

Abbreviations: RL, reflected light; TL, transmitted light

To summarize, hydrothermal magnetite and titanite phases interacting with chalcopyrite±bornite in potassic-altered rocks from all three deposits suggest an important link to Cu-Au mineralization. Further detailed characterization of hydrothermally formed magnetite and titanite is necessary to determine selected PIMs that can be effectively used as prospecting tools for alkalic Cu-Au porphyry deposits.

Future Work

Further work will include a detailed classification and characterization of PIMs from mineral separates obtained from rock samples by electric pulse selective fragmentation (SELFRAG) method. A correlation between petrographic observations and mineral separates made from rock samples is required in order to confirm the PIMs physical parameters that help diagnose hydrothermal activity in alkalic porphyry systems. This will be followed by chemical characterization using a mineral liberation analyzer (MLA) and laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS). Finally, a detailed comparison between physical properties and chemical composition of selected mineral separates and till mineral separates will be explored to determine the feasibility of PIMs as a potential exploration tool for alkalic porphyry deposits in covered regions.

Acknowledgments

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