Coarse muscovite veins and alteration deep in the Yerington batholith, Nevada: Insights into fluid exsolution in the roots of porphyry copper systems

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ABSTRACT

Veins and pervasive wall-rock alteration composed of coarse muscovite±quartz±pyrite are documented for the first time in a porphyritic granite at Luhr Hill in the Yerington district, Nevada. Coarse muscovite at Luhr Hill occurs at paleodepths of ~6-7 km in the roots of a porphyry copper system and crops out on the scale of tens to hundreds of meters, surrounded by rock that is unaltered or variably altered to sodic-calcic assemblages. Coarse muscovite veins exhibit a consistent orientation, subvertical and N-S striking, which structurally restores to subhorizontal at the time of formation. Along strike, coarse muscovite veins swell from distal, mm-thick muscovite-only veinlets to proximal, cm-thick quartz-sulfide-bearing muscovite veins. Crosscutting relationships between coarse muscovite veins, pegmatite dikes, and sodic-calcic veins indicate that muscovite veins are late-stage magmatic-hydrothermal features predating final solidification of the Luhr Hill porphyritic granite. Fluid inclusions in the muscovite-quartz veins are high-density aqueous inclusions of ~3-9 wt% NaCl eq. and <1 mol% CO₂ that homogenize between ~150°C and 200°C, similar to fluid inclusions from greisen veins in Sn-W-Mo vein

systems. Our results indicate that muscovite-forming fluids at Luhr Hill were mildly acidic, of low to moderate salinity and sulfur content and low CO₂ content, and that muscovite in deep veins and alteration differs in texture, composition, and process of formation from sericite at shallower levels of the hydrothermal system. Although the definition of greisen is controversial, we suggest that coarse muscovite alteration is more similar to alteration in greisen-type Sn-W-Mo districts worldwide than to sericitic alteration at higher levels of porphyry copper systems. The fluids that form coarse muscovite veins and alteration in the roots of porphyry copper systems are distinct from fluids that formed copper ore or widespread, shallower, acidic alteration. We propose that this style of veins and alteration at Luhr Hill represents degassing of moderate volumes of overpressured hydrothermal fluid during late crystallization of deep levels of the Yerington batholith.

KEYWORDS: hydrothermal alteration, porphyry copper, Yerington, greisen, muscovite

INTRODUCTION

Deep alteration in the roots of porphyry copper systems reflects fluid evolution within and proximal to a magma chamber. Root zones of porphyry systems are rarely recognized, but Seedorff et al. (2008) documented the presence of coarse muscovite-dominated alteration, referred to as "greisen," as a recently recognized form of deep hydrothermal alteration in the roots of four porphyry copper systems in Arizona (Sierrita-Esperanza, Kelvin-Riverside, Ray, and Miami-Inspiration). Nonetheless, the significance of muscovite veins and alteration in these systems is not well understood, and it is unclear whether coarse muscovite alteration is a common feature in the roots of porphyry copper systems (Seedorff et al. 2005, 2008). This study documents previously unreported coarse muscovite alteration in the Yerington district, Nevada, describes characteristics of associated fluids, and evaluates implications of muscovite veins and alteration in the evolution of this well-exposed Jurassic magmatic-hydrothermal system.

Coarse-grained muscovite alteration had not been described in porphyry copper systems prior to the description of the root zones of four porphyry copper systems in Arizona (Seedorff et al. 2008). Coarse muscovite veins and alteration may be lacking at presently exposed levels of these other systems or may not have been recognized. The porphyry copper systems associated with the Yerington batholith are well studied, and have contributed to genetic models for porphyry copper deposits, and continue to contribute new insights (e.g., Dilles et al. 2015; Halley et al. 2015). In this study, we describe previously unreported deep hydrothermal alteration and coarse muscovite veins in the roots of the Luhr Hill granite and assess their timing and origin. Results suggest that coarse muscovite veins represent late-stage magmatic degassing of acidic fluids that are not related to shallower and higher-temperature forms of alteration. Documentation of coarse muscovite alteration at this well-known porphyry copper locality leads

to the inference that coarse muscovite veins and alteration may be a common feature in the roots of porphyry copper systems.

GEOLOGIC CONTEXT

Structural dismemberment along multiple generations of normal faults are principally responsible for ~90°W tilting that exposed the roots of the Yerington batholith. Multiple porphyry copper centers are exposed in the district, locally to paleodepths of ~7 km (Proffett 1977; Proffett and Dilles 1984; Dilles 1987; Dilles et al. 2000). Fluids that exsolved from the latest phase of the batholith, the Luhr Hill porphyritic granite and related granite porphyry dikes, produced copper ore bodies, such as the Yerington mine that produced roughly 1.7 billion pounds of copper, and voluminous hydrothermal alteration, supplemented by additional alteration produced by convection of external fluids. From shallow to deep, the alteration sequence is broadly zoned from proximal and shallow advanced argillic, underlain by sericitic, then potassic alteration with highest Cu grades. Sodic alteration is widely present at intermediate levels; propylitic alteration distally surrounds porphyry mineralization centers; and sodic-calcic (Na-Ca) alteration occurs at deep levels (3.5 to >6 km) (Carten 1986; Dilles and Einaudi 1992; Dilles et al. 2000).

Luhr Hill is located east of the Singatse Range and southeast of the town of Yerington; alteration at Luhr Hill has not been previously described. Map relationships of normal faults suggest that the study area was originally located below the MacArthur/Bear centers (Dilles and Proffett 1995). The study area at Luhr Hill contains a variety of alteration types. Na-Ca alteration (plagioclase-actinolite-epidote) is the most widespread alteration in the Luhr Hill area (Fig 1) and is similar to that described at deep levels of the Ann-Mason, Yerington, and MacArthur/Bear

porphyry copper centers (Dilles et al. 2000). Aplite and pegmatite dikes crop out throughout the study area. Hydrothermal alteration assemblages that commonly occur at shallower levels in the porphyry copper systems, such as potassic, sericitic, and advanced argillic, do not occur in the vicinity of coarse muscovite alteration at Luhr Hill; the lack of any shallow forms of alteration supports the interpretation that Luhr Hill represents a deep portion of the hydrothermal system.

MUSCOVITE VEINS AT LUHR HILL

Mineralogy

Chemical microanalyses indicate that the white mica in veins and alteration at Luhr Hill is muscovite (Table S1). Muscovite veins range from veinlets 1 mm wide to cm-thick veins containing muscovite-quartz $\pm$ (oxidized) pyrite. In vein halos, hematite $\pm$ pyrite $\pm$ rutile replaces primary magnetite; muscovite and quartz replace K-feldspar; and plagioclase is altered to coarse-grained and fine-grained muscovite and quartz. Muscovite, rutile, hematite, and pyrite replace mafic minerals. Alteration envelopes outside of the veins consist of the same assemblages; pervasive wall-rock alteration of this assemblage extends beyond discrete veins, replacing porphyritic granite with muscovite-quartz and lesser hematite and rutile. Topaz, fluorite, tourmaline, and beryl have not been observed in the muscovite veins at Luhr Hill.

The muscovite in veins at Luhr Hill in some cases forms coarse, euhedral crystals or sprays that protrude into open space within veins, oriented at high angles to the vein walls; muscovite crystals decorate some quartz crystal faces, and quartz surrounds mica sprays (Fig 1; ESM, Table 1). In other places, coarse muscovite forms thin veinlets in which muscovite grains are oriented parallel to vein walls. Coarse muscovite (>1 mm, but commonly several mm to >1 cm across) occurs as envelopes around the veins and as a replacement of feldspar, hornblende,

and biotite in the wall rock. Coarse-grained and fine-grained muscovite also form in vugs and in replacement of feldspar, biotite, and amphibole in pervasive wall-rock alteration. Coarse muscovite composition is fairly low in Al (from 2.02-2.53 apfu Σ Al), high in Fe (from 0.19 to 0.37 apfu Fe), and contain lithophile trace elements such as Li and Cs (Fig 2d; ESM, Table 3).

Vein characteristics and fluid inclusions

The form and mineral assemblage of the veins change along strike: muscovite veinlets 1 mm wide swell to muscovite-quartz-pyrite veins ~1.5 cm wide within ~10 m of strike length (Fig 3). Thicker quartz-bearing muscovite veins are sinuous and contain pyrite whereas muscovite-only veinlets are planar. The veins are thickest, most abundant, and sinuous in the area of the most pervasive muscovite-dominated wall-rock alteration (Fig 1b). Some veins display sinuosity over ~5 m of strike length before becoming planar; the veins maintain the same orientation across the transition from sinuous to planar. Veins strike consistently from 315°-340°, with subvertical dips, with the exception of one outcrop with veins striking 240° and dipping steeply to the north; these orientations restore to subhorizontal at time of emplacement (Fig 1a). Muscovite veins and alteration crosscut most aplite and pegmatite dikes. Though pegmatite and aplite dikes can be observed across Luhr Hill, they are more abundant in eastern exposures and in the vicinity of the muscovite alteration. Many aplite and pegmatite dikes appear to share similar orientations to the muscovite veins; dikes in the area dominantly strike 330°-020° and dip moderately to steeply east (Fig 1a). Muscovite veins offset most Na-Ca (plagioclase-epidote-actinolite) veinlets; the reverse crosscutting age relationship between muscovite and Na-Ca veinlets was rarely observed.

Quartz crystals in muscovite veins from Luhr Hill contain abundant fluid inclusions. Most inclusions are secondary or uncertain in origin, but some assemblages of primary

inclusions were identified (Fig 2). All inclusions (primary, secondary, and those of uncertain origin) are high-density aqueous inclusions containing two fluid phases, liquid plus vapor, at room temperature and lacking daughter minerals (Fig 2c). All inclusions analyzed are of low to moderate salinity (3.5-8.8 wt% NaCl eq.) and contain detectable CO₂. Upon freezing, fluid inclusions exhibit first melting (eutectic) temperatures of approximately -20°C. Ice melting temperatures are in the range of -2 to -6°C, and melting of CO₂-clathrate is from 4.9 to 8.8°C. Clathrate melting occurs in the presence of aqueous liquid and carbonic vapor and without carbonic liquid present. Homogenization to the liquid phase occurs at 137 to 197 °C (ESM, Table 2).

INTERPRETATIONS

Formation of muscovite

Muscovite alteration at Luhr Hill is characterized by coarse grained, commonly euhedral muscovite veins, in alteration envelopes in wall rock, lining vugs both within veins and wall rock, and replacing preexisting minerals in wall rock (Fig 1). These textures suggest that muscovite formed by two different processes: (1) precipitated directly from the hydrothermal fluid into open space and (2) replaced original igneous minerals including feldspar, biotite, and amphibole. The precipitation of coarse muscovite directly from hydrothermal fluids into open space suggests transport of Al in solution, which distinguishes coarse muscovite in this setting at Luhr Hill from sericitic alteration at higher levels. In sericitic alteration, fine-grained muscovite generally forms by replacement of Al-bearing silicates (predominantly feldspars) through hydrolytic removal of cations.

Coarse muscovite in deep exposures of veins and alteration at Luhr Hill is texturally, spatially, and chemically distinct from fine-grained muscovite that characterizes sericitic alteration in shallow portions of the Yerington porphyry copper systems. Coarse muscovite veins and pervasive alteration are only observed in deep exposures of the Yerington batholith (>4 km paleodepth); sericitic alteration is only preserved in shallower exposures of the batholith (typically ≤ 2 km paleodepth, Dilles and Einaudi 1992). Orientations of Luhr Hill muscovite veins restore to subhorizontal at the time of emplacement, whereas sericitic veins present at higher levels restore to subvertical (Dilles and Einaudi 1992); this indicates lithostatic pressure at the time of coarse muscovite vein emplacement, which reflects the difference in depth of formation between shallow sericitic and deep coarse muscovite alteration. Luhr Hill muscovite also shows compositional distinctions in both major and trace elements from sericitic muscovite analyzed from elsewhere in the Yerington district; Luhr Hill muscovite contains more Fe, less Al, lower $\text{Mg}/(\text{Mg} + \Sigma\text{Fe})$, and higher lithophile element concentrations than sericitic muscovite (Fig 2d; Cohen 2011). Enrichment in lithophile elements is expected in late-stage fluids as incompatible elements concentrate in residual melt (Candela and Piccoli 2005).

Paleodepths and timing of fluid release

Coarse muscovite veins and alteration at Luhr Hill formed at paleodepths of ~6-7 km, matching the deepest exposures of Na-Ca alteration but well below the copper ore bodies in the district (Proffett 2008). Crosscutting relationships suggest that muscovite veins postdate most Na-Ca veins and alteration, although it predates a few Na-Ca veins at Luhr Hill, indicating that these veins formed late in the evolution of the porphyry copper system. Na-Ca alteration and coarse muscovite alteration postdates many aplite and pegmatite dikes in the Luhr Hill area. In the Yerington district, Na-Ca alteration reflects influx of externally derived brines that alternate

with expulsion of magmatic fluids (Carten 1986; Dilles and Einaudi 1992; Dilles et al. 1992, 1995, 2000). Timing relationships, therefore, suggest that coarse muscovite veins formed from fluids released late in the evolution of the batholith, between influxes of external brines.

The small volume of muscovite alteration, represented by the areal extent of alteration (Fig 1a), suggests modest volumes of muscovite-forming fluid. This restricted extent indicates that at the exposed surface fluids equilibrated with feldspar-bearing wall rocks over a paleovertical distance of only ~100 m. When restored to the time of formation, almost all muscovite veins at Luhr Hill are sub-horizontal, implying fluid pressures exceeding lithostatic load (Fournier 1999). Horizontal veins are also reported at greisen-bearing Sn-W vein deposits such as Panasqueira and Zinnwald, where Sn-W veins display both vertical and horizontal orientations (Kelly and Rye 1979; Webster et al. 2004; Neiva 2008). One exposure at Luhr Hill exhibits muscovite veins with paleovertical orientations; its location within the most pervasive area of muscovite-dominated wall-rock alteration (Fig. 1a) suggests that this exposure may represent a feeder zone.

Temperatures and compositions of fluids

Presence of pyrite and fluid inclusion compositions indicate that muscovite-forming fluids at Luhr Hill were of low to moderate salinity and sulfur content and low CO₂ content. Pressure corrections yield formation temperatures of 230°-300°C at 6 km paleodepth to 245-315°C at 7 km paleodepth, assuming lithostatic load of 27 MPa/km. First-melting temperatures indicate that Na±K dominate the cation load and that the fluids lack significant divalent cations (e.g., Ca or Fe). Lack of boiling, based on consistent phase ratios in all fluid inclusions, is reasonable given the significant depths and likely lithostatic pressure conditions. Consistency of primary and secondary fluid inclusions suggests that fluid properties remained similar during

formation of muscovite veins, which may reflect exsolution of the muscovite-forming fluids from a late-stage and highly fractionated (granite minimum) melt.

Though remaining fairly consistent over this time, it is possible that these low temperatures result from long-term storage, as temperatures may have cooled significantly from magmatic temperatures. It is also possible that the low temperatures inferred for muscovite vein and alteration formation (~230-315°C) at Luhr Hill are due to magmatic-hydrothermal fluids undergoing substantial cooling between exsolution from melt and vein formation or that the fluids were exsolved from a supercooled (subsolidus) melt (London 2008). Sinuous parts of muscovite veins likely formed at higher temperatures, based on the interpretation that the sinuous texture is related to minor ductile deformation. The thinner, planar parts of veins likely formed at cooler temperatures outward from the source. The spatial association between muscovite veins and pegmatite and aplite dikes (Fig 1) may suggest that muscovite-forming fluids exsolve from a supercooled pegmatitic melt or a small volume of evolved, relict melt prior to final solidification of the batholith. Certain pegmatite dikes were crosscut by muscovite at Luhr Hill, whereas other dikes were observed without muscovite alteration. It is likely that these pegmatite and aplite dikes emanated from a larger, deeper source at or near aqueous saturation and would have continued to exsolve fluids until fully crystallized. Preliminary observations at other muscovite locations hosted in the roots of porphyry copper systems in Arizona (e.g., Globe-Miami, Sierrita, Ray) suggest a potential link between pegmatites and muscovite veins. It is possible though less likely that muscovite veins formed from fluid exsolved from a younger, more felsic intrusion that is not observed spatially related to the muscovite alteration at Luhr Hill.

DISCUSSION

Geological and geochemical environment of muscovite alteration at Luhr Hill and comparison to greisen at other deposits

We compare the mineral assemblage, orientation, and fluid inclusion compositions of the coarse muscovite veins and alteration at Luhr Hill to well documented, coarse muscovite-dominated greisen alteration in Sn-W-Mo deposits. There are key similarities and differences between the muscovite veins and alteration at Luhr Hill and greisen at classic tungsten-vein localities (Neiva 2008; Lecumberri-Sanchez et al. 2015). The mineral assemblages at Luhr Hill and in classic tungsten-vein localities both lack major Fe and Ca minerals, contain open space-filling textures, and are dominated by muscovite-quartz assemblages. Muscovite-forming fluids at Luhr Hill have salinity (3-9 wt%) and CO₂ concentrations (<1 mol%) that are broadly similar to vein fluids at typical Sn-W systems (Wood and Samson 2000). At Luhr Hill, muscovite is the major F-bearing phase, as opposed to topaz or fluorite, and the muscovite-dominated alteration does not contain Sn or W mineralization. Hydrothermal precipitation of coarse muscovite with similar major-element composition is common to both types of systems, but trace element and ore metal endowments differ markedly; these differences likely reflect differing magma composition and associated redox state (Černý et al. 2005; Seedorff et al. 2005).

The term greisen has multiple connotations, as greisen is used both for (1) a type of mineral deposit, such as greisen Sn-W-Mo deposits, and (2) a type of vein and alteration envelope (e.g., Shcherba 1970; Černý et al. 2005). Alteration types are mineral assemblages that formed in similar geological and geochemical environments (Meyer and Hemley 1967). Where the controversial term greisen is used in the second context, as a type of vein or alteration, various definitions are used including those that emphasize (1) a more restrictive definition

characterized by mineral assemblage and texture, typically coarse-grained muscovite and quartz with essential accessory F-, B-, or Be-rich phases (Lindgren 1933), (2) texture, for coarse-grained white mica plus quartz, with or without other minerals (cf., Shaver 1991), or (3) a mineralogical and chemical definition that excludes any reference to grain size (e.g., Burt 1981).

The similarity of coarse muscovite veins and alteration at Luhr Hill to greisen alteration in Sn-W-Mo vein systems is based on association with coarse muscovite-quartz, total replacement of wall rock, and open space-filling textures in related veins; the similarities extend to major-element compositions of minerals, fluid inclusion characteristics, and vein orientations.

The presence or absence of certain accessory phases largely reflects differences in compositions of the associated magmas; minerals rich in F (e.g., topaz, fluorite), B (e.g., tourmaline), Be (e.g., beryl), Sn (e.g., cassiterite), or W (e.g., scheelite, wolframite) occur in greisen veins and alteration produced by peraluminous and felsic metaluminous intrusions (e.g., Barton 1987; Černý et al. 2005) but not in rocks of less felsic bulk compositions, such as the Yerington batholith.

The occurrences of coarse muscovite veins and alteration in the roots of porphyry copper systems vary both within districts, as documented here for Luhr Hill, and between districts. The most important points, however, are that (1) the muscovite veins and alteration at the roots of porphyry copper systems differ from those formed at higher levels, most notably those that contain sericite; (2) many veins and altered rocks from the roots of porphyry copper systems are mesoscopically similar to veins and altered rocks in greisen-type deposits worldwide, such as Panasqueira (e.g., Kelly and Rye 1979); and consequently (3) the geological and geochemical environment of the roots of porphyry copper systems, including Luhr Hill, is more similar to that of greisen Sn-W-Mo deposits than to the shallow levels of porphyry copper systems. As noted

earlier (Seedorff et al. 2005), these observations have practical implications for porphyry copper exploration: sericitic alteration occurs largely within and above ore bodies, whereas coarse muscovite alteration occurs largely below ore bodies.

Petrologic implications

Late-stage magmatic hydrothermal fluids exsolved from intermediate magmas that are capable of forming porphyry copper systems evolve with the crystallization and evolution of the melt. Late-stage fluids create alteration that more closely resembles alteration associated with more highly evolved metaluminous and peraluminous granites but lacks the accessory phases commonly observed in greisen-type alteration developed in greisen-type deposits. The ore-forming fluid in a porphyry copper deposit represents a relatively late-stage product, based on phenocryst abundances of 35-55 vol% in porphyry intrusions (Dilles 1987; Seedorff et al. 2005); nonetheless, >40% of the magma chamber continues to crystallize following exsolution of fluids that form copper mineralization. We infer that coarse muscovite alteration is the product of fluids released during crystallization of this remaining portion of the batholith. Though few studies have characterized porphyry copper root zones, coarse muscovite veins and alteration have now been identified in all districts where root zones have been studied in detail. Efficient scavenging of metals from the magma chamber by fluids during the earlier events that form porphyry copper ore bodies, and the absence of such preceding events in the Sn-W-Mo systems, may account in part for coarse muscovite veins and alteration at Luhr Hill being poorly endowed in copper, whereas similar veins in Sn-W-Mo systems are rich in cassiterite and/or wolframite.

CONCLUSIONS

This description of veins and related alteration at Luhr Hill is the first documentation of deep, coarse, muscovite±quartz±pyrite in the Yerington district; these veins and alteration precipitated under overpressured fluid conditions at ~230-315°C late in the crystallization history of the Yerington batholith. Coarse muscovite veins and alteration formed after release of moderate volumes of mildly acidic magmatic-hydrothermal fluids of low to moderate salinity and sulfur content and low CO₂ content. These fluids equilibrated with feldspar-bearing wall rocks over a paleovertical distance of ~100 m and are distinct from earlier fluids that formed copper ore or shallower sericitic alteration. The coarse muscovite alteration bears similarities to the greisen style of alteration in Sn-W-Mo deposits, and differences may reflect origin from a magmatic system with a less felsic bulk composition than the Sn-W-Mo deposits. The presence of coarse muscovite alteration in the Yerington district suggests that coarse muscovite alteration is a common characteristic of the roots of porphyry copper systems. We concur with suggestion by Seedorff et al. (2008), that coarse muscovite alteration in the deep roots should be appended to zonation of alteration for porphyry copper systems (Lowell and Guilbert 1970; Sillitoe 2010).

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REFERENCES CITED

- Barton MD (1987) Lithophile-element mineralization associated with Late Cretaceous two-mica granites in the Great Basin. *Geology* 15: 337-340
- Burt, DM (1981) Acidity-salinity diagrams—Applications to greisen and porphyry deposits. *Econ Geol* 76: 832-843
- Candela PA, Piccoli PM (2005) Magmatic processes in the development of porphyry-type ore systems. *Econ Geol 100th Anniv Vol*: 25-37
- Carten RB (1986) Sodium-calcium metasomatism: Chemical, temporal, and spatial relationships at the Yerington, Nevada, porphyry copper deposit. *Econ Geol* 81: 1495-1519
- Černý P, Blevin PL, Cuney M, London D (2005) Granite-related ore deposits. *Econ Geol 100th Anniv Vol*: 337-370
- Cohen JF (2011) Compositional variations in hydrothermal muscovite and chlorite from wall-rock alteration at the Ann-Mason porphyry copper deposit, Nevada. Master's thesis, Oregon State University, 138 pp
- Dilles JH (1987) Petrology of the Yerington batholith, Nevada: Evidence for evolution of porphyry copper ore fluids. *Econ Geol* 82: 1750-1789
- Dilles JH, Einaudi MT (1992) Wall-rock alteration and hydrothermal flow paths about the Ann-Mason porphyry copper deposit, Nevada - a 6-km vertical reconstruction. *Econ Geol* 87: 1963-2001

- Dilles JH, Proffett JM (1995) Metallogensis of the Yerington batholith, Nevada; Porphyry Copper Deposits of the American Cordillera. Arizona Geol Soc Digest 20: 306-315
- Dilles JH, Solomon GC, Taylor HP Jr., Einaudi MT (1992) Oxygen and hydrogen isotope characteristics of hydrothermal alteration at the Ann-Mason porphyry copper deposits, Yerington, Nevada. Econ Geol 87: 44-63
- Dilles JH, Farmer GL, Field CW (1995) Sodium-calcium alteration by non-magmatic saline fluids in porphyry copper deposits: Results from Yerington, Nevada. Mineralogical Association of Canada Short Course 23: 309-338
- Dilles JH, Einaudi MT, Proffett JM Jr., Barton MD (2000) Overview of the Yerington porphyry copper district: Magmatic to nonmagmatic sources of hydrothermal fluids: Their flow paths and alteration effects on rocks and Cu-Mo-Fe-Au ores. Soc Econ Geol Field Guide 32: 55-66
- Dilles JH, Kent AJR, Wooden JL, Tosdal RM, Koleszar A, Lee RG, Farmer LP, 2015, Zircon compositional evidence for sulfur-degassing from ore-forming arc magmas. Econ Geol 110: 241-251
- Einaudi MT, Burt DM (1982) Introduction—Terminology, classification, and composition of skarn deposits. Econ Geol 77: 745-754
- Fournier RO (1999) Hydrothermal processes related to movement of fluid from plastic into brittle rock in the magmatic-epithermal environment. Econ Geol 94: 1193-1211
- Halley SW, Dilles JH, Tosdal RM (2015) Footprints: Hydrothermal alteration and geochemical dispersion around porphyry copper deposits. SEG Newsletter 100: 1, 12-17
- Jackson NJ, Moore JM, Rankin AH (1977) Fluid inclusions and mineralization at Cligga Head, Cornwall, England. Jour Geol Soc Lond 134: 343-349

- Kelly WC, Rye RO (1979) Geologic, fluid inclusion, and stable isotope studies of the tin-tungsten deposits of Panasqueira, Portugal. *Econ Geol* 74: 1721-1822
- Lecumberri-Sanchez P, Pinto F, Vieira R, Wälle M, Heinrich CA, Beralto S, 2015, Tin-tungsten mineralizing processes in tungsten vein deposits: Panasqueira, Portugal [abs.]: AGU Fall Meeting 2015, San Francisco.
- Lindgren W (1933) *Mineral Deposits*. McGraw-Hill Book Company, Inc., New York, 930 pp
- London D (2008) Pegmatites. *Can Mineral Spec Publ* 10, 347 pp
- Lowell JD, Guilbert JM (1970) Lateral and vertical alteration-mineralization zoning in porphyry ore deposits. *Econ Geol* 65: 373-408
- Meinert LD, Dipple GM, Nicolescu S (2005) World skarn deposits. *Econ Geol* 100th Anniv Vol: 299-336
- Meyer C, Hemley JJ (1967) Wall rock alteration. In Barnes HL (ed) *Geochemistry of hydrothermal ore deposits*. Holt, Rinehart, and Winston, New York, pp 166-235
- Neiva AMR (2008) Geochemistry of cassiterite and wolframite from tin and tungsten quartz veins in Portugal. *Ore Geol Rev* 33: 221-238
- Proffett JM Jr. (1977) Cenozoic geology of the Yerington district, Nevada, and implications for the nature and origin of Basin and Range faulting. *Geol Soc Am Bull* 88: 247-266
- Proffett, JM Jr. (2009) High Cu grades in porphyry Cu deposits and their relationship to emplacement depth of magmatic sources. *Geology* 37: 675-678
- Proffett JM Jr., Dilles JH (1984) Geologic map of the Yerington district, Nevada. *Nev Bur of Mines and Geol Map* 77
- Seedorff E (1988) Cyclic development of hydrothermal mineral assemblages related to multiple intrusions at the Henderson porphyry molybdenum deposit, Colorado. In Taylor RP,

- Strong DF (eds) Recent advances in the geology of granite-related mineral deposits.
Canadian Inst Mining Metall Spec Vol 39: pp 367-393
- Seedorff E, Dilles JH, Proffett JM Jr., Einaudi MT, Zurcher L, Stavast WJA, Johnson DA,
Barton MD (2005) Porphyry deposits: Characteristics and origin of hypogene features.
Econ Geol 100th Anniv Vol: 251-298
- Seedorff E, Barton MD, Stavast WJA, Maher DJ (2008) Root zones of porphyry systems:
Extending the porphyry model to depth. Econ Geol 102: 939-956
- Shaver SA (1991) Geology, alteration, mineralization and trace element geochemistry of the Hall
(Nevada Moly) deposit, Nye County, Nevada. In: Raines GL, Lisle RE, Schafer RW,
Wilkinson WH (eds) Geology and ore deposits of the Great Basin. Geol Soc Nevada
Sym, Reno/Sparks, 1990, Proc: pp 303–332
- Shcherba GN (1970) Greisens. Internat Geol Rev 12: 114-150
- Sillitoe RH (2010) Porphyry copper systems. Econ Geol 105: 3-41
- Webster J, Thomas R, Forster H-J, Seltnann R, Tappen C (2004) Geochemical evolution of
halogen-enriched granite magmas and mineralizing fluids of the Zinnwald tin-tungsten
mining district, Erzgebirge, Germany. Miner Deposita 39: 452-472
- Williams PJ, Barton MD, Johnson DA, Fontboté L, de Haller A, Mark G, Oliver NHS, Marschik
R (2005) Iron oxide copper-gold deposits: Geology, space-time distribution, and possible
modes of origin. Econ Geol 100th Anniv Vol: 371-405.
- Wood SA, Samson IM (2000) The hydrothermal geochemistry of tungsten in granitoid
environments: I. Relative solubilities of ferberite and scheelite as a function of T, P, pH
and m_{NaCl} . Econ Geol 95: 143-182

FIGURE CAPTIONS

Fig 1 Coarse muscovite veins and alteration at Luhr Hill, Yerington district, Nevada. (a) Alteration map of the northeastern corner of Luhr Hill. (b) Muscovite veins at Luhr Hill with quartz (qz) – pyrite (py) centerline and inner muscovite (m) envelopes with dashed lines to show the extent of muscovite-quartz alteration. (c) Muscovite vein with open-space filling textures. (d) Muscovite spray in quartz-muscovite vein from Luhr Hill (plane-polarized, transmitted light)

Fig 2 Petrography of greisen veins. (a) Quartz-muscovite vein from Luhr Hill (plane-polarized, transmitted light). A quartz crystal contains two sub-parallel fluid inclusion assemblages. (b) Cathodoluminescence showing growth bands in quartz from 2a. (c) Quartz-hosted fluid inclusion assemblage from Luhr Hill greisen veins: high-density aqueous inclusions with consistent phase ratios and no daughter minerals. (d) Compositions of micas from coarse muscovite alteration at Luhr Hill (this study; LH = Luhr Hill greisen) compared to those of other alteration assemblages at Yerington (Cohen 2011; WS = weak sericitic; Ser = sericitic; S-C = sericite-chlorite; Ill = illite; AA = advanced argillic)

Fig 3 (a) Schematic cross section of coarse muscovite veins at Luhr Hill in Jurassic, pre-tilt view. (b) Bull quartz veins ≤ 15 cm thick with thin muscovite-pyrite envelopes are relatively shallow. (c) Thin, planar, muscovite veinlets occur deep and outboard from system center, thickening along strike to (d) proximal cm-thick quartz-muscovite-sulfide veins