Root Zones of Porphyry Systems: Extending the Porphyry Model to Depth

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Abstract

The root zone of a porphyry system is a specific region beneath a porphyry orebody that was a site of focused fluid flow, as evidenced by abundant quartz veins, widespread wall-rock alteration, or porphyry dikes merging downward into a porphyritic granite cupola. These zones constitute an important source region of ore fluids and other components, and in certain geologic terrains the characteristics of root zones may point to previously undiscovered deposits.

The root zones of four Laramide porphyry copper systems in Arizona recently have been characterized at a reconnaissance level: the Miami Inspiration system associated with the Schultzte Granite, the Siercita- Esperanza system associated with the Ruby Star Granodiorite, the Ray system associated with the Granite Mountain pluton, and the Kelvin-Riverside system associated with the Tea Cup pluton. The two well-studied root zones related to the Jurassic Yerington batholith in Nevada, and associated with the Yerington mine and the Ann-Mason deposit, provide a basis of comparison. All six systems occur in areas with unusually large exposures in both lateral and vertical paleodirections, locally to paleodepths of >10 km, because of postore extensional faulting and associated tilting. No two systems are alike, but many share the presence of the following hydrothermal characteristics: quartz veins and potassic alteration, sodic-calcic and sodic alteration, calcic alteration, and relatively coarse grained muscovite-quartz (greisen). Quartz veins and potassic alteration are focused centrally, directly above related cupulas; sodic-calcic and sodic alteration, calcic alteration, and evidence for leaching of silica are observed on the deep flanks of certain systems; and greisen occurs directly beneath ore within and beneath coeval cupulas in many systems. Certain systems exhibit evidence of multiple cycles of release of magmatic fluid followed by incursion of saline ground waters, which are analogous to the biological cycle of exhale-inhalce, respectively.

The characteristics of the root zones provide important constraints on the exsolution and transport of the magmatic aqueous phase that leads to ore formation, the variable incursion of external fluids into the hydrothermal system, and the degassing of magmatic volatiles that may not be related directly to porphyry ore formation. The most robust conclusions are drawn from the localities that offer the greatest quality of exposure and degree of continuity (including compelling structural reconstructions) between the roots and the ore deposit, from the studies that identify timelines linking processes in the roots with those in the mineral deposit, and from systems in which the deposit itself is well characterized.

Introduction

EXPLORATION programs designed to discover porphyry deposits typically employ models that contain both empirical and genetic components (Sillitoe and Thompson, 2006). Despite the diversity of porphyry systems, porphyries are widely considered to be among the best modeled deposit types. Since publication of the influential paper on tops and bottoms of porphyry copper deposits (Sillitoe, 1973), the tops of porphyry systems (i.e., the region above the ore deposits) have been investigated extensively. The tops of active and late Cenozoic systems can be observed in modern arcs, with varying degrees of confidence in the genetic linkage between the shallow environment and an underlying porphyry deposit (Einaudi et al., 2003). The upper levels of systems can contain clues about the nature of the underlying porphyry system (Hedenquist and Lowenstern, 1994; Keith et al., 1997; Seedorff et al., 2005a). In many geologic terrains, porphyry systems are explored almost exclusively “from the top down.”

Many aspects of the porphyry orebodies themselves are poorly understood, as a recent review demonstrates (Seedorff et al., 2005a). For instance, the space-time links between different vein types in single deposits typically are not well known. Likewise, the distribution of metals within and near orebodies is generally poorly documented, such that the causes for different shapes of orebodies are not well known, and our understanding of the controls on metal zoning in porphyry deposits is rudimentary. In addition, we have a poor understanding of the controls for the evolutionary paths of fluids (e.g., why much of the copper is deposited in potassic alteration assemblages with bornite ± magnetite in certain porphyry copper deposits, whereas in other deposits the potassic assemblages are barren and most of the copper is deposited at lower temperature in sericitic assemblages as chalcopyrite + pyrite; Seedorff and Einaudi, 2004b). None of these aspects of porphyry systems is incorporated explicitly in models of porphyry deposits.

The bottoms of systems (i.e., the region below the ore deposits) are rarely described, yet multiple lines of evidence indicate that the metal-bearing fluids that precipitated metals in porphyry deposits rose from below (e.g., Gustafson and Hunt, 1975; Burnham, 1979; Dilles, 1987; Carten et al., 1988; Redmond et al., 2004). The magmatic systems likely continue for many kilometers beneath the orebody, into and perhaps beneath a cognetic batholith. A critical region is the root zone of the hydrothermal system, where porphyry bodies broke through the crystalline carapace of cupulas on the underlying magma chamber during their rise to shallower levels (Carten, 1986; Dilles and Einaudi, 1992).
This contribution describes the distinctive features of root zones of porphyry systems based on simplified descriptions of six examples, with an emphasis on new work by the authors and their collaborators on four examples in Arizona (Fig. 1). We discuss the relationship of root zones to higher levels in the system and the diversity and complexities that result from the dynamic and three-dimensional nature of porphyry systems. Certain distinctive features in the roots may be the deep manifestation of the ore-forming process at higher levels, whereas others largely may be unrelated to ore formation. If the characteristics of root zones and their adjacent flanks are incorporated into porphyry exploration models, then it becomes possible to explore for ore virtually “from the bottom up” or “from the sides inward,” as may be required in terrains that are complicated by postore structure or deeply incised topographically (Maher et al., 2005).

Depth Constraints and Value of Tilted Sections

In order to constrain the depth in magmatic-hydrothermal systems, stratigraphic and structural markers are needed to guide geologic reconstructions, or geochemical constraints are required from mineral or fluid inclusion barometry. Most porphyry deposits formed within 1 to 6 km of the surface, but a few may have formed as deep as 10 km (Seedorff et al., 2005a). Without depth constraints, it may not be possible to distinguish between the deep portion of a system that was emplaced at normal to shallow levels (e.g., top of orebody at 2 km) versus a system that was emplaced entirely at deep levels (e.g., top of orebody at 6 km).

Few porphyry systems have a vertical exposure of more than 2 km (fig. 9 of Seedorff et al., 2005a). In compact deposits such as the Henderson porphyry molybdenum deposit, this may encompass the entire orebody and barren regions above and below. In the largest porphyry copper deposits, however, the orebody may extend for several kilometers vertically, beyond the levels of exposure, including the deepest drill holes (e.g., Gustafson and Quiroga, 1995). The complete porphyry system, ranging from the paleosurface to underlying magma body or bodies, has much greater dimensions than the orebody in all porphyry deposits, regardless of class of deposit or size ranking within the class. The porphyry systems that have known vertical exposures significantly greater than 2 km (e.g., Yerington and Ann-Mason in the Yerington district, Nevada; Dilles et al., 2000; Sierrita-Esperanza: Stavast et al., 2008) occur within tilted sections created by normal faulting and associated tilting (Seedorff et al., 2005a). In these systems, the present map view generally represents one or more cross-sectional or oblique sectional views through the crustal column at the time of ore formation (Seedorff et al., 2005a). Nonetheless, porphyry systems such as Cadia, New South Wales (Holliday et al., 2002), Kerr, British Columbia (Bridge et al., 1996), and

FIG. 1. Location maps. A. Map of southwestern North America, showing the limit of the Basin and Range province, the schematic representation of domains that were highly extended by Tertiary normal faulting, the positions of Cordilleran metamorphic core complexes, and the locations of porphyry copper deposits, with the Yerington district labeled (modified from Seedorff, 1991; Dickinson, 2002). B. Simplified geologic map of southern Arizona (see A for location), with locations of four root zones in Arizona and the cities of Phoenix, Tucson, and Nogales labeled (modified from Barton et al., 2005a).
Potrerillos, Chile (Olson, 1989), were dismembered in contractional tectonic settings, juxtaposing different levels of a system across reverse faults (Seedorff et al., 2005a).

The root zone, here, refers not just to the pluton that is co-genetic with a porphyry deposit, but rather to specific regions beneath porphyry orebodies that were sites of focused fluid flow, as evidenced by abundant quartz veins, widespread wall-rock alteration, or porphyry dikes merging downward into a porphyritic granite cupola. Previous workers in certain circumstances seem to use root zone to refer to the vicinity of the bottom of the orebody (Durning and Davis, 1978), but the cupola and associated root zone of the hydrothermal system generally are located at still deeper levels by a kilometer or more. In certain districts, such as the Robinson (Ely, Ruth) district in eastern Nevada, a large body of granite or porphyritic granite that was co-genetic with the ore-related porphyries has been identified (the Weary Flat pluton of Bauer et al., 1966; Westra, 1979; Seedorff et al., 1996), yet the root zone of that system may be eroded, not yet exposed, or otherwise unrecognized.

The classic examples of root zones are in the Yerington district, Nevada (Figs. 1, 2A, B, 3A, B), where several Jurassic porphyry copper deposits related to the Yerington batholith are tilted ~90° to the west, primarily as a result of Miocene and younger normal faulting (Proffett, 1977; Geissman et al., 1982; Proffett and Dilles, 1984; Dilles et al., 2000). Both the Yerington mine and Ann-Mason deposits are exposed continuously in cross-sectional view downward, in the Jurassic frame of reference, from above the top of the orebody into the root zone. Tilted sections of Laramide (latest Cretaceous to early Tertiary) porphyry copper systems, dismembered and variably rotated by mid-Tertiary and younger normal faulting, are exposed in southern and central Arizona (Maher et al., 2002, 2005; Stavast et al., 2008), where the root zones of the Miami Inspiration, Sierrita-Esperanza, Ray, and Kelvin-Riverside deposits have been identified (Figs. 2C-F, 3C-F). The Arizona systems are the subject of ongoing studies of their structure, petrology, geochronology, space-time evolution of hydrothermal alteration, and geochemical evolution.

**Descriptions of Root Zones**

Table 1 summarizes the characteristics of the two Jurassic systems from the Yerington district in Nevada and the four Laramide systems in southern and central Arizona, which are further described below.

**Igneous characteristics**

In those porphyry systems that have the appropriate exposures, the associated igneous rocks exhibit characteristic changes in texture as a function of depth (Ambrus, 1977; Carten, 1986; Carten et al., 1988). The groundmass grain size in mineralized porphyry intrusions tends to coarsen with depth, with the texture eventually becoming seriate, then porphyritic with a hypidiomorphic-granular matrix, and finally hypidiomorphic-granular or granitic. Individual porphyry intrusions are distinct bodies at the level of the ore deposit, the intrusion of each generally coincident with a discrete fluid release event, but these stocks or dike swarms merge downward into the same underlying pluton (Dilles, 1987). This domal region, known as the cupola (Emmons, 1927; Dilles, 2000), is exposed in relatively few districts. Rock fabrics indicate that rocks in the cupola were subjected to transient periods of ductile deformation (Maher et al., 2005). There also is local evidence in granitic rocks for miarolitic cavities that might have contributed to synmagmatic porosity (cf. Candela and Blevin, 1995; Candela and Piccoli, 2005).

The Luhr Hill Granite phase of the Yerington batholith, inferred to be the source of both the Yerington mine system (Fig. 2A) and the Ann-Mason system (Fig. 2B), is a large, relatively homogeneous unit (Dilles, 1987). Sierrita-Esperanza is related to a megacyclic phase of the Ruby Star Granodiorite (Fig. 2D), a large, homogeneous mass of hornblende-biotite granodiorite (Lovering et al., 1970; Stavast et al., 2008). The Schultze Granite at Miami Inspiration (Fig. 2C) and the Granite Mountain pluton near Ray (Fig. 2E) are both nearly hornblende-free biotite granites. Although the Schultze Granite has a number of small intrusive units, both the Schultze and Granite Mountain plutons contain large, compositionally homogeneous masses (Barton et al., 2005a). The co-genetic intrusion for the Kelvin-Riverside system, the Tea Cup pluton (Fig. 2F), has a hornblende-biotite granodioritic upper phase and a more silicic, biotite granodiorite beneath it (Barton et al., 2005a).

**Hydrothermal characteristics**

The six porphyry systems considered in this study (Fig. 1) illustrate the diversity of hydrothermal characteristics that should be incorporated in models of the bottoms of porphyry copper systems (Table 1).

The terminology for alteration types, largely summarized from Seedorff et al. (2005a), is presented in Table 2. Note that calcic alteration is characterized by garnet, pyroxene, plagioclase, and epidote in igneous protoliths. Calcic alteration described here is similar to endoskarn (cf. Einaudi and Burt, 1982; Barton et al., 1991), but the term endoskarn is used only where hydrothermal exchange across contacts between igneous and carbonate rocks has occurred, with formation of endoskarn-skarn couplets. In other cases of calcic alteration, there is no evidence for carbonate protoliths in the vicinity. Note also that the term greisen is used here, following Shaver (1991), Reed (1997), Seedorff and Einaudi (2004a), and Seedorff et al. (2005a), only as a textural modifier for coarse-grained aggregates, generally of muscovite, quartz, and other minerals. Thus, fluorine-bearing species (other than muscovite), such as topaz, need not be present for altered rock to constitute greisen. Conversely, not all altered rocks with fluorine-bearing minerals constitute greisen.

**Yerington mine:** As documented by Carten (1986), there are two stacked cupolas at the Yerington mine (Figs. 2A, 3A, 4A). Several early, well-mineralized series of porphyry dikes emanate from the older, shallower cupola. Potassic alteration and associated quartz, biotite, and magnetite veins are developed intensely along the axis of the early dikes. Sodic-calcic alteration and associated quartz, plagioclase, tourmaline, and actinolite veins are localized along the crest and flanks of the shallower cupola (Figs. 2A, 3A). Potassic and sodic-calcic alteration were broadly contemporaneous, but crosscutting relationships in the vicinity of the crest of the older, shallower cupola indicate that sodic-calcic alteration was superimposed on potassic alteration at any given site (Carten, 1986).
FIG. 2. Present-day simplified geologic maps, all at the same scale, showing lithology and structure of the six porphyry copper systems discussed in the text, simplified from references cited in the text. Although the systems are not reconstructed (unfaulted, untilted), each map is oriented such that the top of the system at the time of formation is up on the page (the orientation of north arrows varies between panels), so that the maps represent approximate cross sections or oblique sections through each system. Although certain views span more than one fault block, approximate paleodepths near the top and bottom of the exposed portions of systems are shown: A. Yerington mine, Yerington district, Nevada. B. Ann-Mason deposit, Yerington district, Nevada. C. Miami Inspiration system, Globe-Miami district, Arizona. The view emphasizes the root zone, and the western edge of the mine is at the top of the figure. D. Sierrita-Esperanza system, Arizona. E. Ray system, Ray (Mineral Creek) district, Arizona; note that the western edge of the mine is at top of the figure. F. Kelvin-Riverside district, Arizona. The Kelvin prospect lies east of present exposure of cupola on Tea Cup pluton; the Riverside portion of the system lies at structurally higher levels of the map, farther to the east.
FIG. 3. Present-day simplified geologic maps, all at the same scale, showing alteration overlays for the six porphyry copper systems discussed in the text, for which the lithology and structure are shown in Figure 2. Abbreviations for alteration: Biot = biotitic; Ca(-Na) = calcic ± sodic types, including calcic alteration; H+ = hydrolytic alteration, including sericite- and chlorite-bearing sericite types; H+(-Na) = hydrolytic and sodic types, including sericite and sodic types; Greisen = muscovite-rich greisen; K-Ca(-Fe-Na) = transitional potassic-calcic and lesser sodic and iron oxide-rich; Kf = K-feldspar; Na = sodic; Na-Ca = sodic-calcic; Na-Fe-H = transitional sodic and iron-oxide-rich alteration containing albite, chlorite, and specular hematite ± magnetite. A. Yerington mine, Yerington district, Nevada. B. Ann-Mason deposit, Yerington district, Nevada. C. Miami Inspiration system, Globe-Miami district, Arizona. D. Sierrita-Esperanza system, Arizona. E. Ray system, Ray (Mineral Creek) district, Arizona. F. Kelvin-Riverside district, Arizona; greisen muscovite veins (not shown) are weakly developed at deep levels.
### Table 1. Summary of Root Zones of Selected Porphyry Systems

<table>
<thead>
<tr>
<th>Porphyry system, associated pluton</th>
<th>Igneous rocks</th>
<th>Calcic alteration</th>
<th>Sodic-calcic and sodic alteration</th>
<th>Quartz veins and potassic alteration</th>
<th>Greisen muscovite</th>
<th>Comments</th>
<th>Principal reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yerington mine, Yerington batholith</td>
<td>Luhr Hill Granite (a hornblende-biotite granite) and related porphyries</td>
<td>Not reported</td>
<td>Intensely developed and widespread</td>
<td>Quartz veins fairly widely distributed, including in cupola</td>
<td>Not reported</td>
<td>Two stacked cupolas present</td>
<td>Carten (1986)</td>
</tr>
<tr>
<td>Ann-Mason, Yerington batholith</td>
<td>Luhr Hill Granite (a hornblende-biotite granite) and related porphyries</td>
<td>Endoskarn present, in part predating emplacement of porphyry dikes</td>
<td>Intensely developed and widespread</td>
<td>Quartz veins associated primarily with potassic alteration and late sodic assemblages</td>
<td>Not reported</td>
<td>Excellent exposures beneath and lateral to orebody</td>
<td>Dilles and Einandi (1992)</td>
</tr>
<tr>
<td>Sierrita-Esperanza, Ruby Star Granodiorite</td>
<td>Megacrystic phase of Ruby Star pluton (a hornblende-biotite granodiorite) and related porphyries</td>
<td>Not reported</td>
<td>Intensely developed but pattern is asymmetrical; leaching of silica observed</td>
<td>Quartz veins with K-feldspar envelopes present</td>
<td>Muscovite ± (pyrite) veins weakly developed</td>
<td>Exposures to paleodepths of ~12 km</td>
<td>Stavast et al. (2008)</td>
</tr>
<tr>
<td>Kelvin-Riverside, Tea Cup pluton</td>
<td>Upper phase of the Tea Cup pluton (a hornblende-biotite granodiorite) and related porphyries</td>
<td>Locally present on flanks of system</td>
<td>Widespread sodic alteration but sodic-calcic is only locally developed on flanks; leaching of silica observed locally</td>
<td>Quartz veins with K-feldspar envelopes present but mostly restricted to top of cupola</td>
<td>Muscovite ± (pyrite) veins weakly developed</td>
<td>Prospects present but no known orebody; exposures to ~12 km paleodepth; flanks contain abundant iron oxide-rich assemblages</td>
<td>Barton et al. (2005a)</td>
</tr>
<tr>
<td>Ray, Granite Mountain pluton</td>
<td>Granite Mountain pluton (a hornblende-poor biotite granite) and related porphyries</td>
<td>Not reported</td>
<td>Not reported</td>
<td>Quartz + (chalcopyrite ± pyrite) veins with K-feldspar envelopes extend beneath orebody into cupola</td>
<td>Muscovite ± (pyrite) veins widespread and intensely developed</td>
<td>Barton et al. (2005a)</td>
<td></td>
</tr>
<tr>
<td>Miami Inspiration, Schultz Granite</td>
<td>Schultz Granite (a hornblende-poor biotite granite) and related porphyries</td>
<td>Not reported</td>
<td>Not reported</td>
<td>Quartz ± (chalcopyrite ± pyrite) veins with K-feldspar envelopes present in granite</td>
<td>Muscovite ± (pyrite) veins ± K-feldspar envelopes widespread</td>
<td>Maher et al. (2005)</td>
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</tbody>
</table>
A late series of weakly mineralized porphyry dikes that emanates from the younger, deeper cupola cuts through the Yerington mine (Carten, 1986). Potassic alteration is localized along the late dikes, although it is developed less intensely than along the early, well-mineralized dikes. Another zone of sodic-calcic alteration is developed along the crest and flanks of the deeper cupola (Figs. 2A, 3A). As in the case of the shallower cupola, crosscutting relationships indicate that sodic-calcic alteration was superimposed on potassic alteration near the crest of the deeper cupola. Between the two cupolas, complex superposition of alteration events with reversals in crosscutting relationships is recorded (e.g., potassic alteration...
### TABLE 2. Characteristics of Selected Alteration Types in Porphyry Copper Deposits

<table>
<thead>
<tr>
<th>Processes or type of chemical reaction, Alteration type</th>
<th>Definition</th>
<th>Characteristics</th>
<th>Spatial distribution</th>
<th>Distinguishing features</th>
</tr>
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<tbody>
<tr>
<td><strong>Volatile addition</strong> Propylitic</td>
<td>Weakly metasomatized rocks with addition of volatiles, such as CO₂ and H₂O</td>
<td>Presence of relict ksp in rocks of granitic composition, with ab, ca, ep, and a dusting of ser, ill, or mont after plag; chl ± act after mafic minerals, with local relict bio; paucity of iron sulfide and oxide minerals; ore minerals scarce to absent</td>
<td>Generally distal to orebody</td>
<td>Chl and ep present, relict ksp ± mt, ore minerals scarce; ca, ep, spec, and chl veins present with ill-defined propylitic envelopes</td>
</tr>
<tr>
<td><strong>Hydrolysis</strong> Sericitic type, classic sericitic variety</td>
<td>Moderate to strong hydrolytic alteration in the muscovite (ser) stability field on T vs. K/H diagram, i.e., precursor ksp (igneous or hydrothermal) altered to ser (fine-grained K-mica, diam &lt;1 mm) + qtz; other phases may substitute for ser</td>
<td>Both precursor ksp (if present) and plag altered to ser; if additional cations and anions are abundant because of composition of fluid or rock, then other phases, including chl, may substitute for ser; pyritic opaque assemblages are most common, but can be mineralized with cp or bn; less commonly, may contain mt or spec</td>
<td>Variable; ranging from a hoodlike zone largely above potassic alteration to an upward-expanding, funnel-shaped zone that extends well above the orebody but also penetrates deeply into potassic alteration</td>
<td>Fine-grained, commonly pyritic, feldspar-destructive alteration envelopes, usually containing ser (fine-grained K-mica), but chl substitutes for ser in mafic rocks; strong regional structural control of veins and associated alteration is common</td>
</tr>
<tr>
<td>Sericitic type, greisen variety</td>
<td>Moderate to strong hydrolytic alteration in the muscovite stability field on T vs. K/H diagram; precursor ksp altered to musc (diam &gt;1 mm) + qtz</td>
<td>In the lower parts of orebodies where potassic alteration dominates, may occur as cp + py veins with musc + qtz envelopes; in root zones that have sparse greisen, occurs generally as thin, sulfide-poor, py-bearing veins, ~1 mm wide, which may have thin outer potassic envelopes (plag altered to ksp); in root zones with abundant greisen, tends to occur as veins, generally tens of cm wide, that change character along strike from musc + qtz aggregates with no vein filling to pod-like vein fillings of qtz + sulfides with alteration halos of qtz + musc ± sulfides</td>
<td>Broad zone centered on cupola, below ore zone but sometimes extending upward into base of the orebody</td>
<td>Coarse-grained, grayish to greenish white K-mica (diam &gt;1 mm) in sheeted sets of veins, ranging from thin veins to wider zones with local, podlike cores of qtz + sulfides</td>
</tr>
<tr>
<td><strong>Alkali exchange</strong> Potassic</td>
<td>Ksp stability field on T vs. K/H diagram, most commonly expressed as precursor lhb and px altered to aggregates of fine-grained (shreddy) bio and precursor plag altered to ksp</td>
<td>Generally most intensely developed in vicinity of highest density of qtz ± sulfide veinlets and/or hairline bi and/or mt veinlets; lhb phenocrysts commonly pseudomorphed by shreddy bio, with ca, fl, or anh, mt, or other Fe-Ti oxides; hydrothermal ksp may occur in qtz veinlets and as replacements of plag as envelopes on qtz veinlets; may be barren, but in many deposits bolch of ore is associated with potassic alteration, as ep, bn, or dig</td>
<td>Proximal, in some (but not all) systems is largely coincident with ore-grade mineralization; partial biotitization may extend hundreds of meters beyond and beneath the limit of ore</td>
<td>Shreddy bio in amphibole and px phenocryst sites; magmatic bio sites may also be partially recrystallized and have more Mg-rich compositions; narrow ksp envelopes after plag on qtz veins; fine-grained hydrothermal bio may also occur in other mineral sites, e.g., plag</td>
</tr>
<tr>
<td>Sodic-calcic</td>
<td>Moderate to strong metasomatism in which hydrothermal sodic plag (commonly olig) replaces precursor ksp; hydrothermal act, chl, ep, and tit replace precursor bio and mt</td>
<td>Generally associated with act and ep veinlets; when intensely developed, can result in massive qtz + act + sodic plag + tit; vuggy texture produced if silica is leached; in porphyry copper systems, commonly is sulfide-poor and int-destructive; results in depletion of K, Fe, Cu relative to fresh rock</td>
<td>Present in root zone, generally concentrated on upper flanks of cupola, beneath and lateral to orebody</td>
<td>Generally as strongly bleached envelopes on narrow green, act- or ep-rich envelopes, i.e., white stripes through darker wall rock; where intensely developed, may produce massive, hard, light-colored, plag-rich rock, though will be somewhat vuggy if silica has been leached</td>
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TABLE 2. (Cont.)

<table>
<thead>
<tr>
<th>Processes or type of alteration, chemical reaction, Alteration type</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Sodic</td>
<td>Ab replace ksp and plag; chl, ep, Qtz, py, and tour veins with envelopes of ab + chl; Proximal, cutting through Weakly bleached zones containing ab and ab with py and/ or ho ser, tour, and py replace mafic more distal occurrences may contain spec ± mt ± orebody and extending to and chl with py and/or spec minerals; lower temperature sulfides with chl ± ab envelopes higher levels, where it may than sodic-calcic alteration grade upward into sericitic alteration and laterally into more iron-rich, chloritic assemblages.</td>
<td>Present in root zone, generally concentrated on flanks of cupola.</td>
<td>Generally waning somewhat laterally to weathering and commonly within the orebody.</td>
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<tr>
<td>Calcic</td>
<td>Metasomatic addition of Ca, characterized by gt, plag, act, calc-silicate minerals; similar to endoskarn except that concentrated on flanks of the cupola and K, characterized by calc-silicates, bio, gt, diop, act, ep, apatite, anh, and ca; lateral to potassic alteration, ... known from commonly within the orebody bio in igneous protoliths porphyry copper systems associated with alkalic rocks.</td>
<td>Presence of both propylitic and calcic assemblages such as at Ann-Mason, Yerington, and the higher levels (Carten, 1986). Neither calcic alteration nor greisen alteration is reported from any of the exposures at Ann-Mason.</td>
<td>Related to younger dikes cutting sodic-calcic alteration formed near the shallower cupola. After all porphyry dikes were emplaced, sericitic alteration was developed at higher levels of the system coupled with sodic alteration at deeper levels (Carten, 1986). Neither calcic alteration nor greisen alteration is reported from any of the exposures at the Yerington mine. <strong>Ann-Mason:</strong> The Ann-Mason deposit (Figs. 2B, 3B) lies only a few kilometers southwest of the Yerington mine. The Ann-Mason system is related to a separate cupola on the Luhr Hill Granite phase of the Yerington batholith, and cross sections (Proffett and Dilles, 1984) indicate that the Ann-Mason orebody formed about 1.5 km deeper than the system at the Yerington mine. The exposure of the root zone, especially in the lateral direction, is larger at Ann-Mason than at the Yerington mine (Fig. 2A, B). As documented by Dilles and Einaudi (1992), the highest copper grades at Ann-Mason are associated spatially with granite porphyry dikes and with quartz veins, potassic alteration, molybdenite, and high Cu/Fe ratio sulfides. Weak biotitic alteration also occurs in the upper part of the cupola beneath the orebody (Fig. 3B). Sodic-calcic alteration extends to depths of at least 3 km below and laterally to 3 km beyond the copper orebody, and endoskarn occurs in an even more distal position (Fig. 3B). Lateral to the orebody, sodic-calcic alteration extends from several kilometers above the flanks of the cupola to a few hundred meters into the cupula itself (Fig. 3B). As at the Yerington mine, sodic-calcic and potassic alteration developed broadly contemporaneously with emplacement of porphyry dikes, whereas propylitic alteration formed at higher levels in distal positions. <strong>Late-stage alteration,</strong> postdating emplacement of porphyry dikes at Ann-Mason, is confined largely to a shallow, funnel-shaped volume in the axial portion of the hydrothermal system, in part superimposed on main-stage alteration. The latestage alteration grades upward and outward from assemblages of sodic, transitional sodic-sericitic, and sericitic types (Dilles and Einaudi, 1992). Greisen alteration is not reported from any of the exposures at Ann-Mason. <strong>Miami Inspiration:</strong> All of the porphyry copper systems in the Globe-Miami and Superior districts, which are exposed in the Pinal Mountains and vicinity, appear to be related to phases of the Schultz Granite. These include the vein and manto deposits of the Magma mine, the Resolution (Magma porphyry) and Superior East porphyry deposits, the Cactus-Carolita, Castle Dome-Pinto Valley, Bluebird-Oxhide-Miami Inspiration-Miami East, Copper Cities-Diamond H, and Old Dominion deposits (Peterson, 1962; Hammer and Peterson, 1968; Breitrick and Lenzi, 1987; Sell, 1995; Manske and Paul, 2002). The Schultz Granite is complexly faulted and variably tilted, but a deeply exposed zone in the Pinto Creek area (Figs. 2C, 3C) is interpreted on the basis of structural reconstruction to be the roots of the Miami Inspiration deposit, which contains potassic and sericitic alteration (Maher et al., 2005; Stavast, 2006). As described by Maher et al. (2005) and Stavast (2006), the root zone at Pinto Creek contains sheeted sets of quartz ± K-feldspar ± biotite ± (pyrite &gt;&gt; chalcopyrite) veins with local K-feldspar envelopes that cut the Schultz Granite. Ductile shear zones are present in the pluton at these levels, locally deforming earlier-formed brittle veins (Fig. 4E, F). Greisen muscovite ± (pyrite) veins</td>
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propylitic alteration is absent to rare. Neither sodic-calcic alteration nor calcic alteration has been reported in the roots of quartz ± (pyrite >> chalcopyrite). Neither sodic-calcic alteration nor calcic alteration has been reported in the roots of quartz ± (pyrite >> chalcopyrite). Neither sodic-calcic alteration nor calcic alteration has been reported in the roots of quartz ± (pyrite >> chalcopyrite). Neither sodic-calcic alteration nor calcic alteration has been reported in the roots of quartz ± (pyrite >> chalcopyrite). Neither sodic-calcic alteration nor calcic alteration has been reported in the roots of quartz ± (pyrite >> chalcopyrite). Neither sodic-calcic alteration nor calcic alteration has been reported in the roots of quartz ± (pyrite >> chalcopyrite). Neither sodic-calcic alteration nor calcic alteration has been reported in the roots of quartz ± (pyrite >> chalcopyrite). 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low (e.g., Hildreth, 1981; Taylor and McLennan, 1985); hence, metals must be extracted efficiently from a large volume of felsic magma via a mechanism such as convective flow of the magma toward the cupola. The Yerington batholith (Dilles, 1987) and reconnaissance investigations of the plutons in the Arizona examples (except for possibly the Tea Cup pluton, which to date has resulted in well-mineralized prospects but no porphyry copper ore deposit; Figs. 2E, 3E) suggest that the plutonic phase associated most closely with porphyry ore formation was large and fairly uniform in both composition and texture (Fig. 2C-E). This observation is consistent with the magma chambers being convectively well mixed. In a few porphyry systems, such as Bingham, there is evidence for transient, metal-rich input from mafic to ultramafic rocks (Keith et al., 1997, 1998; Core et al., 2006). Although there are small amounts of gabbro exposed in the Yerington district (Dilles, 1987) and monzodiorite exposed above the south side of the Tea Cup pluton (Barton et al., 2005a), direct evidence for introduction of mafic magmas into the felsic magma chambers largely is lacking at all of the systems considered here, despite the ideal surface exposures to observe them. Moreover, the radio metrically dated diorite rocks exposed in the region containing the Arizona examples are a few million years older than the porphyry systems (Sedorff et al., 2005b).

Exsolution and transport of magmatic aqueous phase

Numerous mechanisms potentially could result in formation of ore in porphyry systems, each of which makes predictions that can be tested in the field or laboratory.

The aqueous phase may not have exsolved from the magma until the porphyry body was emplaced (e.g., Carten et al., 1988). The onset of saturation with the aqueous phase may have caused the magma to stop rising and to crystallize. The deepest occurrence of geologic features that record the magmatic-hydrothermal transition, such as unidirectional solidification textures (USTs) (e.g., Shannon et al., 1982; Kirwin, 2005), could mark the base of aqueous phase separation. Hydrothermal features such as quartz veins and metal-bearing fluid inclusions should only be present near the apex of the porphyry stock or dike swarm and should be lacking at deeper levels between the stock and underlying cupola. The challenge of this type of model is to generate a large volume of aqueous phase that apparently is required to form an ore deposit from a small intrusion, especially at deposits such as Butte and El Teniente, where the known volume of porphyry is miniscule (e.g., Meyer et al., 1968; Cannell et al., 2005).

The challenge of this model may be overcome by continued delivery of aqueous phase from a large subjacent magma chamber to the top of a porphyry stock via a narrow column.
of vertically convecting magma (Shinohara et al., 1995). In this case, hydrothermal features should be present at least locally along the deep flanks of the stock, between the base of the orebody and the underlying cupola.

A third scenario in which a porphyry deposit might form is by passive degassing of a magma chamber. The flux of metal-bearing fluids being emitted from volcanoes such as White Island (Hedenquist et al., 1993; Rapien et al., 2003) is adequate to transport sufficient metals to form a deposit over a geologically realistic time interval of tens of thousands of years. The challenge, however, is to apply such a model to porphyry deposits to explain the typically close association of the ore zone to the apices of individual porphyry intrusions.

A large volume of aqueous phase first may have collected in the cupula, then may have been turbulently entrained as a water-rich three-phase mixture (crystals, melt, and aqueous phase) as the magma and aqueous phase rose together to the site of ore deposition. A variation on this theme is for a mass of less dense aqueous phase to advance ahead of a rising body of magma, hydraulically wedging open the overlying rock. In these cases, in which aqueous phase is delivered to the site of ore deposition cataclysmically, one might expect vein formation and ore deposition to be developed along the entire path of porphyry emplacement, between the cupula and the orebody.

Another challenge is to explain why rise of porphyry magma was halted, preventing eruption at the surface and focusing ore over the apex of a porphyry intrusion. Features such as USTs and other internal contacts, discordance in foliations or other ductile features, and truncation of veinlets, which may provide evidence to distinguish between the various scenarios, commonly are quite subtle and require careful, detailed mapping to identify and document. Laboratory tests have comparable challenges. For example, fluid inclusions commonly exhibit complex superposition and lack of definitive evidence for primary origin (e.g., Seedorff and Einaudi, 2004b), although careful cathodoluminescence (CL) imaging of quartz might allow separation of events (e.g., Rusk and Reed, 2002). Some of the systems with the best geologic constraints, such as Yerington, are notorious for having fluid inclusions that provide little information about the high-temperature history of the system (e.g., Price, 1977; Dilles and Einaudi, 1992). Attempts to do fluid inclusion work at Sierrita to date also have failed to yield usable inclusions (e.g., Klemm, 2005).

**Inursion of nonmagmatic saline fluids into root zones**

Depending on the compositions of the magmas associated with the magmatic hydrothermal systems, sodic-calcic alteration can have variable fluid sources. In fenites and certain gneisens environments, sodic alteration is clearly the product of magmatic fluids (e.g., Barton et al., 1991). In porphyry copper systems, some workers also have inferred a magmatic origin for sodic-calcic alteration (e.g., Lang et al., 1985a, b). Especially for the calc-alkaline porphyry copper systems, such as the six considered here, the evidence favors an external source of fluids for sodic-calcic alteration, as discussed further below.

During the release of magmatic fluids, fluid pressures at or exceeding lithostatic values may be maintained near the apex of a mineralizing intrusion (Fournier, 1999; Cox, 2005), commonly producing early, high-temperature veins with both steep radial and gently outward-dipping orientations (e.g., Carten et al., 1988). Associated hydrofracturing in many cases probably allows a quick drop in pressure toward hydrostatic levels. The orientations of later veins (including greisen muscovite and sodic-calcic assemblages) tend to reflect the regional stress field (e.g., Rehrig and Heidrick, 1972; Maher et al., 2005) and to follow dikes (e.g., Dilles et al., 2000). The fractures that control the orientation of late veins probably are generated by forces associated with differential cooling, as well as by a deviatoric component generated by the magma chamber on the surroundings. Field evidence and theoretical considerations suggest that dense brines, such as a saline basinal or surface-derived external fluid or a recirculated magmatic brine (Fig. 5A), may gain access via hydrostatic circulation to the central, high-temperature portion of a hydrothermal system (Hanson, 1996; Fournier, 1999). Indeed, evidence from hydrothermal systems such as the Skaggsland complex indicate that incursion of external fluids can occur at temperatures exceeding 500°C (e.g., Norton and Taylor, 1979; Manning and Bird, 1986; Bird et al., 1985).

The hallmark of ingress of external saline fluids in porphyry systems is the development of sodic-calcic alteration (Dilles et al., 1995; Fig. 5A, B). Although sodic-calcic and sodic alteration are quite common on a global basis, especially associated with iron oxide copper-gold (IOCG) deposits (e.g., Barton et al., 1991; Battles and Barton, 1995; Barton and Johnson, 2000), the number of recognized occurrences that are clearly porphyry related are relatively few (see compilations in Carten, 1986; Dilles et al., 1995). The fluids that produced sodic-calcic and sodic alteration at Yerington (Dilles et al., 1992, 1995) and at occurrences not known to be related to porphyry systems (e.g., Battles and Barton, 1995) had δ18O values higher than those of typical magmatic waters and were moderately to highly saline, consistent with the geologic evidence at many locales for incursion of saline nonmagmatic fluids (Fig. 5). Nannomagmatic saline brines could originate either from (1) contemporaneous near-surface brines formed in playas or salars in areas with arid climates, (2) formation waters derived from older evaporites in wall rocks, or (3) contemporaneous seawater.

The two Yerington examples and two of the four Arizona examples are associated with sodic-calcic and sodic alteration on the deep flanks of the system (Figs. 3, 5). At the southern end of the Yerington district (Fig. 3B) and locally within the broad areas of sodic-calcic alteration at Kelvin-Riverside (Fig. 3F), igneous rocks are converted to calc-silicate assemblages, which is evidence of calcic metasomatism and involvement of external fluids. Vuggy textured granitoid rocks, in which the quartz sites have been leached preferentially, have been observed at least locally within areas of most intense sodic-calcic alteration. Such leaching of quartz is consistent with the quartz-poor nature of veins related to sodic-calcic alteration and unequivocal evidence that the associated fluids were following a thermally prograding path (i.e., were being heated as they flowed downward and inward toward the cupula: Hennelly et al., 1980; Fig. 4).

The new Arizona examples suggest that sodic-calcic alteration may be fairly common in porphyry copper systems if deep levels were exposed (Fig. 5B). Given the genetic links
between saline fluids and sodic-calcic alteration (Fig. 5A, B), many porphyry systems globally may have sodic-calcic alteration at depth, considering that many of the world’s porphyry deposits either formed beneath a paleosurface in an arid climate or were emplaced into wall rocks that contain evaporite beds formed during older periods of aridity. For example, the Atacama region of the Andes has been generally arid since at least the Jurassic (Arcuri and Brimhall, 2002), and Tertiary evaporites of gypsum and halite formed in settings analogous to the modern Salar de Atacama (Mortimer, 1973; Alpers and Brimhall, 1988). Evaporites are common in Permain, Triassic, and Jurassic strata in western North America from the present-day Sierra Nevada to the Rocky Mountains (Butler, 1971; Dickinson, 1989; Battles and Barton, 1995) and occur in the wall rocks of deposits such as Sierra-Re Esperanza (beyond the eastern edge of Figs. 2D, 3D) and Yerington (Fig. 2B). Even though sodic-calcic alteration may be more common in porphyry copper systems than recognized previously, the volume of sodic-calcic alteration in porphyry systems is dwarfed by its volume in many IOCG systems (Barton and Johnson, 1996; Johnson, 2000). Although the processes by which sodic-calcic alteration is generated in porphyry and IOCG systems are similar (Fig. 5A), sodic-calcic alteration plays a nonessential, accessory role in porphyry systems (e.g., Dilles et al., 1995). By contrast, sodic-calcic alteration plays an essential role in ore formation in IOCG systems, where classic porphyry-style features are absent (e.g., Barton and Johnson, 1996; Johnson and Barton, 2000). Nonetheless, a general overlap of IOCG and porphyry systems in time and space occurs in some regions (Barton et al., 2005b).

**Evidence for possible sodic-calcic alteration at depth**

In the systems where sodic-calcic alteration is exceptionally well developed in root zones, fingerlike projections of sodic-calcic alteration locally may extend upward into the base of the orebody, as at the Yerington mine and Ann-Mason (Fig. 3A, B). Even if sodic-calcic alteration sensu stricto does not extend all the way into the orebody, there might be clues near the base of orebodies that sodic-calcic alteration could be present at depth.

Assemblages that can be termed transitional between sodic-calcic, sodic, calcic, and potassic alteration types (see Seedorff et al., 2005a, for discussion of transitional alteration types) are common within and near the base of the same orebodies that exhibit sodic-calcic alteration, even though published descriptions and simplified alteration maps (e.g., Fig. 3) tend to group these with potassic assemblages. For example, epidote is a common constituent of many K-feldspar- and biotite-bearing mineral assemblages at both Ann-Mason (e.g., epidote in biotitic assemblages: Dilles and Einaudi, 1992) and Sierra-Re Esperanza (e.g., epidote or chlorite in veins with orthoclase and quartz, and albite in veins with orthoclase and quartz: West and Aiken, 1982). These transitional assemblages may have formed where external fluids coming in from the flanks of the system were mixing with upwelling magmatic fluids (Fig. 5).

In many systems where the root zones are not exposed, transitional assemblages occur that may be analogous to the occurrences at Ann-Mason and Sierra-Re Esperanza. In the deep portions of El Salvador, Chile, sodic minerals such as sodic plagioclase and calcic minerals such as actinolite, epidote, apatite, anhydrite, calcite, and titanite become part of mineral assemblages with K-feldspar and/or biotite (Gustafson and Quiroga, 1995). Albite is a prominent mineral in several transitional potassic-sodic assemblages that contain K-feldspar, biotite, and/or topaz, which occur near the base and sides of the Seriate ore zone in the porphyry molybdenum deposit at Henderson, Colorado (Seedorff and Einaudi, 2004a, b). Albite, anhydrite, and apatite occur with K-feldspar and/or biotite at Toquepala, Peru (Zweng and Clark, 1995). Albite occurs in various assemblages at Rosario in the Collahuasi district, Chile, in some cases with K-feldspar and/or biotite but in other cases with magnetite and/or copper-iron sulfides (Clark et al., 1998). A barren biotite-albite-magnetite assemblage was formed early at Cerro Colorado, Chile (Bouzari and Clark, 2006). There could be wall-rock compositional controls on some of these occurrences (i.e., mafic rocks would favor development of calcic or sodic minerals over potassic minerals). However, this cannot be the explanation in cases such as Henderson, where the host rocks are everywhere high-silica rhyolite (Seedorff and Einaudi, 2004a, b), and it is highly unlikely in cases such as El Salvador, where appearance of transitional mineral assemblages with depth is not related to a change in host-rock composition (Gustafson and Quiroga, 1995). The possibility that external fluids or recirculated magmatic brines introduced by earlier mineralizing intrusions (e.g., Seedorff and Einaudi, 2004a; Fig. 5A) mixed with magmatic fluids should be tested for these deposits and be examined in detail at all systems where root zones are exposed. The importance of careful documentation of mineral assemblages (including analyses of feldspars) cannot be overemphasized if these genetic questions are to be addressed adequately.

**Evidence for multiple cycles of release of magmatic fluid and incursion of saline ground water**

The extent to which multiple events observed in an orebody are also recorded in the root zone may be highly variable. For example, numerous cycles of hydrothermal activity with associated vein and alteration patterns may be recorded by crosscutting relationships in the proximal, high-temperature environment of a magmatic-hydrothermal system, such as the Henderson porphyry molybdenum deposit (Seedorff and Einaudi, 2004a) or the Birch Creek lithophile element system (Barton, 2000), whereas the distal, low-temperature expression of the same system, only a few hundred meters away, may be recorded as one event with a single zone of concentration.

Of the six systems in Arizona and Nevada summarized here, numerous cycles of alteration-mineralization have been documented at the level of the orebody at the Yerington mine and Ann-Mason, each related to emplacement of a generation of porphyry dikes (Dilles et al., 2000), and analogous behavior has been suggested at Sierra-Re Esperanza (West and Aiken, 1982; Herrmann, 2001; Stavast, 2006; Stavast et al., 2007) and at Ray (D.A. Johnson and M.D. Barton, unpub. mapping, 2003). At the level of the root zone, the Yerington mine is the only one of these systems that clearly exhibits multiple centers, where there are two vertically stacked cupolas (Figs. 2A, 3A). The possibility of multiple centers in other
root zones is suggested, however, by alteration patterns at Ray (Fig. 3E) and reversals in crosscutting relationships at Miami Inspiration (Maher et al., 2005). Crosscutting relationships between veins associated with potassic and sodic-calcic alteration at the Yerington mine indicate that the root zone was dominated alternately by magmatic and external fluids, respectively (Carten, 1986), and similar relationships are evident in the root zone of Sierrita-Esperanza (Stavast, 2006; Stavast et al., 2007).

Magmatic centers can be regarded as sources of perturbations to the regional ground-water flow regime in aquifers that constitute the source of external fluids in magmatic-hydrothermal systems. The shallow crust, be it along an active arc (Rech et al., 2002) or in miogeoclinal rocks of the Great Basin (Burbey and Prudic, 1991), constitutes a regional ground-water system that is recharged under the influence of topography over thousands of years. The compositions of ground waters depend on the compositions of both the surface waters and the rocks of the aquifers through which the ground waters flow. The compositions of surface waters are a strong function of the local climate, which is influenced by factors such as latitude, orographic effects, and global temperature cycles that vary on geologically short time scales. For example, the Great Basin has shifted in the last 10,000 years from a cold, moist climate with large fresh-water lakes at the end of the last ice age to a warm, dry climate with saline plays today (Oviatt, 1997; Adams and Wesnosky, 1998; Rhode et al., 2005). By comparison, major magmatic centers and volcanic fields have life spans ranging from hundreds of thousands to a few millions of years (Hildreth, 1981; Hildreth and Lanphere, 1994).

Therefore, a large flux of magmatic fluid should prevent temporarily the passage of external fluids through the intrusive center. Eventually, the regional flow of ground water near the intrusive center will be reestablished, and external fluids will penetrate the heart of the magmatic system if they are sufficiently dense, albeit heated by proximity to magma (Fig. 5A). In the presence of saline ground-water systems, one might predict, therefore, that magmatic centers with multiple intrusions might exhibit a cycle with alternating release of magmatic fluids followed by incursion of external brines during their evolution, analogous to the biological cycle of exhale-inhale, respectively. Additional documentation of crosscutting relationships between various types of veins and between veins and intrusive contacts in the root zones of hydrothermal systems is required to assess the importance of this process.

Greisen in porphyry copper systems and presence of acidic fluids at depth

Muscovite-rich greisen veins are common in the ore zones of porphyry molybdenum deposits of the quartz monzonitic-granitic porphyry Mo-Cu subclass (Shaver, 1991; Seedorff et al., 2005a) but are relatively rare in porphyry copper systems (Williams and Forrester, 1995; Seedorff et al., 2005a). Greisen has been documented in porphyry copper systems within the ore zones at Pinto Valley, Arizona (Breitrick and Lenzl, 1987), and Valley Copper, British Columbia (Casselman et al., 1995). In the root zones, all four Arizona examples contain varying abundances of greisen muscovite beneath the orebodies, but there are no reports of greisen in the two examples from the Yerington district (Fig. 3). Greisen is pyritic and weakly mineralized with copper and other base metals in the root zones but is well mineralized with chalcocite and bornite in the ore zones at Pinto Valley and Valley Copper. There is no indication to date that there is a downflow transition from greisen into feldspar-stable alteration (Figs. 3, 5B). It is possible, but not yet established, that greisen in the root zone extends upward directly into the base of the ore zone, where it becomes better mineralized. The origin of greisen and controls on its presence or absence in the ore zones and root zones of porphyry copper systems have not been investigated.

The stability of muscovite relative to biotite and K-feldspar (e.g., fig. 5 of Seedorff et al., 2005a) is a function of a number of variables, among which composition, acidity, and temperature probably are most important (Hemley and Jones, 1964; Burt, 1981; Barton, 1987). Low temperatures could favor the development of muscovite, and the observation that greisen muscovite veins generally crosscut earlier quartz veins with K-feldspar envelopes and biotite veins in the Arizona examples could reflect such a temperature control. The coarse grain size of white mica in the root zone may be a function of muscovite (as opposed to sericite) forming near the upper thermal stability of white mica, compared to lower temperatures of formation of sericite at higher levels in the system.

Fluids of more acidic compositions (or lower $\alpha_{K}/\alpha_{H+}$) favor the development of muscovite over K-feldspar and biotite. Acidity is likely a factor in forming greisen muscovite in the root zones, but the common presence of outer K-feldspar envelopes (Fig. 4B) and the absence of pervasive K-feldspar destruction (greisen abundances rarely exceed 10 vol % of the rock and commonly are ~1%) suggest that the fluids responsible for forming muscovite were only mildly acidic. The source of acidity, however, remains to be determined.

For fluids of similar temperatures and compositions, magmas and wall rocks of more aluminaous compositions (i.e., peraluminous, as opposed to metaluminoius) favor the development of muscovite. The whole-rock compositions of igneous rocks from the Arizona examples appear to be somewhat more aluminaous than those from the Yerington district, and the compositions of igneous biotites from the Arizona examples also are, on average, slightly more aluminaous than those in the Yerington district (Dilles, 1987; Stavast, 2006). Although the lack of reported greisen muscovite in the Yerington district might be consistent with this explanation, the absence of a zone of K-feldspar or biotite veins in the Yerington district in an analogous position where greisen muscovite is developed in the Arizona examples (Fig. 2) suggests that a separate process may be responsible for the presence of greisen muscovite.

A possible explanation for the lack of a zone of K-feldspar-bearing alteration beneath the zone of greisen muscovite (Fig. 5B) is that acidic fluids formed at high levels in the system were somehow convected downward into the roots of the system. The system-scale alteration patterns (Fig. 3), however, do not provide any evidence for this.

A second possibility is that the greisen-forming fluids largely are unrelated to ore formation and perhaps are related to a late period of passive degassing of the magma chamber.
ROOT ZONES OF PORPHYRY SYSTEMS

Intrusive contacts.

ships among these features and between them and the major abundance of these features in the ore zones and root zones, greisen veins and pegmatite and aplite dikes to porphyry ore leased during periods of saturation. The relationship of vapor saturation and undersaturation and how vapor is re-related magma chambers fluctuate back and forth between having a poor understanding of whether or not porphyry-re-

ration in magma chambers is still poorly understood. We also

have a poor understanding of whether or not porphyry-re-

lated magma chambers fluctuate back and forth between vapor saturation and undersaturation and how vapor is re-

leased during periods of saturation. The relationship of greisen veins and pegmatite and aplite dikes to porphyry ore formation awaits detailed mapping of the distribution and abundance of these features in the ore zones and root zones, coupled with careful documentation of crosscutting relationships among these features and between them and the major intrusive contacts.

Implications for Exploration

Root zones contain the deep manifestation of the ore-forming process at higher levels (Fig. 5). If the root zone of an upright and structurally intact magmatic-hydrothermal system is exposed, then the ore zone has been eroded, and the root zone is of little direct value to an explorationist. If the system is tilted and dismembered, however, then the orebody may be preserved and/or covered, representing an exploration target that could be explored from the bottom up (Maher et al., 2005), beginning in the root zone. A critical requirement, then, is a structural reconstruction of the system.

Porphyry dikes should be followed upward from the cupola in search of an ore zone. In mineralized systems, the region in and above the cupola (Fig. 5B) contains variably mineralized quartz veins with K-feldspar envelopes, hairline K-feldspar veinlets, and biotitic alteration of hornblende sites. Sodic-calcic alteration, calcic alteration, and evidence of leaching of silica are developed best on the deep flanks of cupolas (Fig. 5B), so the direction toward a possible orebody is upward and sideways, toward the region where porphyry dikes may have pierced the apex of a cupola. Localized sources of salinity at the surface or as evaporite beds in wall rocks, or preferential zones of permeability, could cause asymmetric development of sodic-calcic alteration and calcic alteration.

During past exploration of certain Arizona occurrences, we suspect that greisen may have been confused with sericite alteration and, if so, has been misinterpreted as characteristic of the high levels of a system (e.g., Seedorff et al., 2005a). The exploration significance of greisen depends on its mode or modes of origin. If there is an intimate genetic relationship between formation of greisen and ore occurring at higher levels, as suggested by the local occurrence of mineralized greisen at Pinto Valley, then the most prospective systems might be those whose root zones contain well-mineralized greisen. If formation of greisen is not related directly to ore formation and merely reflects degassing during late stages of magmatic evolution, a conclusion that would be consistent with the absence of reports of greisen in the Yerington district, then the exploration implications of greisen are less significant (Fig. 5B).

Summary

Root zones of porphyry systems are sites of focused fluid flow where porphyry dikes cut upward through a porphyritic granite cupula toward overlying porphyry orebodies. Postore extensional faulting and associated tilting in the Tertiary have exposed root zones of six porphyry copper systems in Nevada and Arizona, locally to depths of >10 km: two Jurassic systems in the Yerington district and four Laramide systems in Arizona. Although no two systems are alike, quartz veins and potassic alteration occur directly above related cupolas; many contain greisen muscovite-quartz within and beneath coeval cupolas, and certain systems contain sodic-calcic alteration, calcic alteration, and evidence for leaching of silica on the deep flanks of the systems. The regions beneath orebodies are likely to offer many clues about “what we don’t know” (Skinner, 1997) about the deposits, including the bounds and magnitudes of the ore-forming systems, the depth of the ore-forming systems, and their geologic age and duration. Indeed, many genetic questions are better addressed in the roots than in the orebodies themselves or the tops of systems. The most robust conclusions, however, will be drawn from the localities that offer the greatest degree of continuity (including compelling structural reconstructions) and quality of the exposure (natural and man made) between the roots and the deposit, from the studies that identify (and demonstrate) time lines that link processes in roots with those in the mineral deposit, and from systems in which the deposit itself is well characterized.

Further work on the root zones of porphyry systems undoubtedly will provide interesting insights, as will similar research on tilted examples of other ore deposit types.

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