New evidence of magmatic-fluid–related phyllic alteration: Implications for the genesis of porphyry Cu deposits

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ABSTRACT

The phyllic alteration in a number of circum-Pacific porphyry Cu-Au deposits is related to high-temperature saline magmatic fluids. This contradicts the widely used genetic models wherein phyllic alteration formed as the result of mixing between magmatic and meteoric fluids. At the Endeavour 26 North porphyry deposit in eastern Australia, the transition from early potassic to the main-stage phyllic alteration is associated with fluids that with time decline in total salinity, NaCl/KCl, and temperature from ~600 to ~550 °C. Calculated and measured δ18O and δD compositions of fluids (5.1‰–8.5‰, δ18O, −57‰ to −73‰, δD) confirm a primary magmatic origin for both the early potassic and main-stage phyllic alteration. These results are consistent with other recent studies (e.g., El Salvador, Chile, Far Southeast, Philippines, and Panguna and Porgera, Papua New Guinea) and suggest that, rather than these results being unusual, a major revision of porphyry Cu genetic models is required.

Keywords: copper, gold, magmatic, ore-forming fluids, porphyry.

INTRODUCTION

Porphyry ore deposits form within and adjacent to porphyritic intrusions that are apophyses to larger stocks that have been water saturated within the upper several kilometers of the crust. The intrusions form huge hydrothermal systems of exsolved magmatic fluids with a carapace of convectively circulating meteoric water. They are important not only because they are the world’s largest source of Cu, but also because they provide evidence for how magmas and their hydrothermal systems evolve at shallow depths. Since the appearance of a coherent descriptive model (Lowell and Guibert, 1970), debate has raged over the role meteoric water plays in the development and genetic models to larger stocks that have been water saturated within the upper several kilometers of the crust. The intrusions form huge hydrothermal systems of exsolved magmatic fluids with a carapace of convectively circulating meteoric water. They are important not only because they are the world’s largest source of Cu, but also because they provide evidence for how magmas and their hydrothermal systems evolve at shallow depths. Since the appearance of a coherent descriptive model (Lowell and Guibert, 1970), debate has raged over the role meteoric water plays in the development and genetic models to larger stocks that have been water saturated within the upper several kilometers of the crust. The intrusions form huge hydrothermal systems of exsolved magmatic fluids with a carapace of convectively circulating meteoric water. They are important not only because they are the world’s largest source of Cu, but also because they provide evidence for how magmas and their hydrothermal systems evolve at shallow depths. Since the appearance of a coherent descriptive model (Lowell and Guibert, 1970), debate has raged over the role meteoric water plays in the development and genetic models to larger stocks that have been water saturated within the upper several kilometers of the crust. The intrusions form huge hydrothermal systems of exsolved magmatic fluids with a carapace of convectively circulating meteoric water. They are important not only because they are the world’s largest source of Cu, but also because they provide evidence for how magmas and their hydrothermal systems evolve at shallow depths. Since the appearance of a coherent descriptive model (Lowell and Guibert, 1970), debate has raged over the role meteoric water plays in the development and genetic models to larger stocks that have been water saturated within the upper several kilometers of the crust. The intrusions form huge hydrothermal systems of exsolved magmatic fluids with a carapace of convectively circulating meteoric water. They are important not only because they are the world’s largest source of Cu, but also because they provide evidence for how magmas and their hydrothermal systems evolve at shallow depths. Since the appearance of a coherent descriptive model (Lowell and Guibert, 1970), debate has raged over the role meteoric water plays in the development and genetic models to larger stocks that have been water saturated within the upper several kilometers of the crust. The intrusions form huge hydrothermal systems of exsolved magmatic fluids with a carapace of convectively circulating meteoric water. They are important not only because they are the world’s largest source of Cu, but also because they provide evidence for how magmas and their hydrothermal systems evolve at shallow depths. Since the appearance of a coherent descriptive model (Lowell and Guibert, 1970), debate has raged over the role meteoric water plays in the development...
Homogenization temperatures range from 550 to 640 °C for the early potassic alteration and from 370 to 560 °C for quartz-sericite veining (Table 1). As with most porphyry Cu and Cu-Au deposits (Beane and Bodnar, 1995), early potassic alteration at E26N is characterized by high-temperature, high-salinity inclusions (42 wt% NaCl; 40 wt% KCl; 18 wt% H₂O) derived from magmatic fluids. However, the occurrence of high-temperature and high-salinity inclusions (35 wt% NaCl; 38 wt% KCl; 27 wt% H₂O) in the quartz-sericite veins is not considered to be typical for porphyry deposits, and may also suggest a magmatic origin for such phyllic alteration. This differs from the previous thinking that the sericite stage formed as the result of meteoric water overprinting of the early magmatic system (Taylor, 1997). Phyllic alteration along faults and fractures at E26N is characterized by secondary fluid-inclusion populations that are low temperature (240–320 °C), low salinity, and liquid rich, more characteristic of mixing between meteoric and magmatic fluids (Beane and Titley, 1981) or just the thermal collapse of the magmatic-hydrothermal system (Shinohara and Hedenquist, 1997).

The temporal change from hypersaline fluids associated with early potassic alteration to lower salinity fluids and associated phyllic alteration in most porphyry Cu deposits has been attributed to dilution of the magmatic fluids with meteoric water (Henley and McNabb, 1978). As an alternative to this model, Shinohara and Hedenquist (1997) proposed that the early crystallization of a magma chamber releases a hypersaline brine and low-salinity vapor that form potassic and advanced argillic alteration, respectively. Subsequent crystallization leads to the escape of lesser amounts of low-salinity aqueous magmatic fluids. As these fluids ascend and cool they may travel along a pressure-temperature path that does not intersect their solvus, and in doing so retain the bulk salinity of the original magmatic fluid (Shinohara and Hedenquist, 1997). These low-salinity magmatic fluids will not only result in phyllic alteration through K-metasomatism as the fluids cool, but they may also carry significant concentration of metals (Hedenquist and Richards, 1998).

**OXYGEN AND HYDROGEN ISOTOPE RESULTS**

The δ¹⁸O and δD of sericite and δ¹⁸O of quartz and δD of fluid inclusions in quartz...
range from 4.7‰ to 9.9‰ and from −57‰ to −73‰ (Table 1), respectively, in veins from main-stage, mineralized phyllic (quartz-sericite-anhydrite) alteration (stage 3). Calculated isotopic fluid compositions of the alteration minerals are most similar to K-silicate alteration of other porphyry Cu and Cu-Au deposits, in that the bulk of the samples plot within the magmatic water box (Fig. 1A).

Hedenquist et al. (1998) argued that magmatic water as defined by Taylor (1974) is more appropriately termed residual magmatic water, because it is the water left in a magma upon complete crystallization, i.e., after the majority of the water has exsolved. A simple mass balance demonstrates this. Magmatic fluid that discharges from volcanic fumaroles has a relatively enriched δD composition, ~−20‰ ± 10‰ (Giggenbach, 1992), and the initial melt compositions are between −20‰ and −45‰ (Taylor, 1992). If the typical aqueous fluid-melt fractionation factor (~−20‰; Suzuki and Epstein, 1976) is appropriate, clearly an isotopically depleted fluid remains in the crystallizing magma (Taylor, 1986). The residual, depleted δD fluid will be incorporated in hydroxyl-bearing minerals and/or degassed at a later stage (e.g., Taylor et al., 1983). Continued magma degassing may explain large variations and/or strong depletion of δD (Taylor, 1988) in potassic and phyllic alteration of some porphyry Cu-Au deposits (Fig. 1).

If the exsolved magmatic fluid intersects its solvus, hypersaline liquid and vapor form. Further isotopic fractionation occurs during such boiling (e.g., Horita et al., 1995). We demonstrate this through modeling the evolution of an originally single-phase magmatic fluid with an initial fluid composition of 6.5‰ δ18O and −35‰ δD, and ~10 wt% NaCl at 550 °C (point a in Fig. 1B). As the fluid reaches its solvus, the fluid becomes immiscible and vapor-liquid separation occurs. The vapor has an isotopic composition similar to that exsolved from volcanic fumaroles (Shmulovich et al., 1999). The formation of hydrous minerals through reaction with this vapor will produce mineral assemblages that are enriched in D and depleted in 18O [b(v) in Fig. 1B], whereas reactions with the separated brine would give the opposite effect [b(l) in Fig. 1B]. Subsequent cooling of the brine will result in further depletion of D and 18O as the solvus closes (c in Fig. 1B; e.g., Shmulovich et al., 1999). However, wall-rock interaction and finite reservoir effects will tend to deplete the δ18O fluid composition (Pollard et al., 1991). These competing mechanisms for isotopic fractionation can explain many of the calculated fluid D and 18O compositions in porphyry-related phyllic alteration (Fig. 1B).

OTHER EXAMPLES OF MAGMATIC-FLUID-RELATED PHYLLIC ALTERATION

In their study of the Rio Blanco, El Teniente, and El Salvador deposits of the central Andes, Kusakabe et al. (1990) found that the transition from early potassic into phyllic alteration was accompanied by an enriched δD isotopic composition of the alteration minerals (~−53‰ to ~30‰ δD). They concluded that the phyllic alteration minerals formed through reaction with an evolved magmatic fluid enriched in D as a result of the previous formation of a hydrous potassic alteration assemblage (Kusakabe et al., 1990). Alternatively, these enriched δD values could occur through interaction with an exsolved magmatic vapor.

Stable isotope and fluid-inclusion data for the Panguna porphyry Cu-Au deposit, Bougainville Island (Ford and Green, 1977; Eastoe, 1978), indicate that early potassic alteration resulted from high-temperature (≥500 °C) and high-salinity magmatic fluids. A decline in temperature (500–380 °C), salinity, and the NaCl/KCl ratio of the hydrothermal fluids led to the onset of main-stage quartz veining and Cu-Au mineralization. Associated chlorite-sericite alteration is inferred to be either synchronous with or immediately postdate potassic alteration. Calculated fluid compositions (5‰−8.2‰ δ18O, −39‰ to −53‰ δD) indicate that this alteration probably developed from magmatic, not meteoric, fluids (Fig. 1). Ford and Green (1977) also emphasized this point, stating that they felt it was highly optimistic to propose a meteoric-hydrothermal source for the main-stage phyllic alteration.

At the Far Southeast porphyry Cu-Au deposit, Philippines, Hedenquist et al. (1998) proposed that the isotopic composition of fluid responsible for phyllic alteration (7.7‰−8.8‰ δ18O, −58‰ to −75‰ δD) was the result of late degassed magmatic fluid, which was depleted in D relative to that responsible for potassic alteration. The potassic to phyllic transition was marked by a sharp decline in temperature (≥500 °C to <350 °C), salinity (~50 to <7 wt% NaCl), and pressure from lithostatic to hydrostatic, interpreted to reflect a lower rate of fluid advection from the magma that precluded phase separation (Shinohara and Hedenquist, 1997).

IMPLICATION FOR THE GENESIS OF PORPHYRY Cu-Au DEPOSITS

We have documented that high-temperature and hypersaline fluids are responsible for both the early K-feldspar-biotite (potassic) and overprinting quartz-sericite-anhydrite (phyllic) alteration at E26N porphyry Cu-Au deposit. Although this differs from the traditional porphyry model, where phyllic alteration is peripheral to mineralized potassic alteration (Beane and Bodnar, 1995), it is not unique. Cu-Fe sulfo- and Au-bearing phyllic alteration (sericite-quartz-anhydrite ± illite-chlorite) within and not peripheral to the potassic (biotite ± K-feldspar) altered core has been documented at Alumbrera (Ulrich et al., 2001), Panguna (Ford and Green, 1977), Granisile and Bell (Wilson et al., 1980), El Teniente and Rio Blanco (Kusakabe et al., 1990), Far Southeast (Hedenquist et al., 1998), and Chuquicamata (Ossandon et al., 2001).

At E26N and other porphyry Cu-Au deposits, the transition from early potassic alteration is associated with fluids that with time declined in total salinity, NaCl/KCl, and temperatures from 700 °C to those <550 °C and as low as 250 °C. Quartz saturation occurred at temperatures above 600 °C, with sufficiently high a(K+)/a(Al³⁺) to initially stabilize K-feldspar. A decline in temperature and a(K+)/a(Al³⁺) of the magmatic fluid led to sericite becoming the predominant K-silicate phase during subsequent veining events (e.g., Hemley and Hunt, 1992). At these high temperatures (350 to >700 °C), in relatively oxidized (fO₂ ~NNO to HM buffer) hydrothermal brines, Cu may be transported as an aqueous chloride complex (CuCl²⁻) (Williams et al., 1995, and references therein). Any changes in temperature, pH, and/or oxygen fugacity will result in deposition of Cu-Fe sulfides and Au in phyllic alteration from a number of porphyry deposits would imply that ore metals are exsolved from the magma, rather than sequestered from the wall rock it overprints.

We conclude that mineralization during phyllic alteration in porphyry-related deposits can be generated solely from cooling of exsolved magmatic brines. Furthermore, the thermal and pH conditions required for feldspar destructive alteration need not be a result of meteoric and magmatic fluid mixing, but simply reflect cooling of these exsolved magmatic brines. Although meteoric fluid may mix with magmatic fluids, major incursion occurs only after the advection of magmatic fluid has largely waned. That phyllic alteration in porphyry deposits may be produced from magmatic fluids was long overlooked in genetic models. This was in part due to the voluminous literature published on North American porphyry Cu deposits, where it has been demonstrated that meteoric waters may play a major role (Taylor, 1997, and references therein). However, globally there is increasing evidence relating phyllic alteration predominately to magmatic fluids (e.g., Hedenquist et al., 1998; Richards et al., 1998). This supports a continuum between high-temperature magmatic
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and lower temperature meteoric water–dominated hydrothermal systems in the formation of phyllic alteration. The recognition of high-temperature phyllic alteration during exploration is important because it means that the distribution of alteration zones and mineralization may not fit the expected alteration pattern so often used to focus drilling programs in porphyry environments.

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