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THE MAGMATIC-METEORIC TRANSITION

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ABSTRACT

Circulation of fluids derived from both magmatic and meteoric sources in the shallow intrusive environment is documented by several empirical factors in porphyry copper deposits of western North America. Early in the cooling history of the shallow plutons, fluids circulating in rocks were endogenous. Following consolidation and pervasive fracturing of the central intrusion, the igneous rock was cooled by broad-scale convective circulation of meteoric waters. The transition from magmatic- to meteoric-derived fluid flow in the porphyritic intrusion is monitored by a shift in the hydrogen isotope ratios of silicate minerals, by a sharp decrease in fluid salinity as recorded by fluid inclusions, and by chloritization of earlier-formed biotite.

INTRODUCTION

Burnham and Ohmoto (1980) have defined a transitional stage during the cooling history of a magma that temporally bridges completely-magmatic and completely-hydrothermal events. During this transitional stage, aqueous fluids derived from the crystallizing magma interact with its crystalline and remaining-melt fractions. Another transition during pluton cooling involves the shift from a magmatic to a meteoric origin for fluids that circulate through and adjacent to the shallow intrusions. Several empirical parameters record changes in the behavior, origin, and characteristics of hydrothermal fluids related to the magmatic-meteoric transition. The information presented here is drawn chiefly from studies of porphyry copper deposits, a class of deposits for which abundant data is available to address the problem of magmatic and meteoric fluids in hydrothermal systems, and the transition between them.

In the western United States, porphyry copper systems are usually associated with granodioritic plutons. These subvolcanic intrusions were rapidly emplaced to depths as shallow as 1 to 2 km in an extensional tectonic regime, and some show evidence of volcanic venting (Figure 1). Several workers have

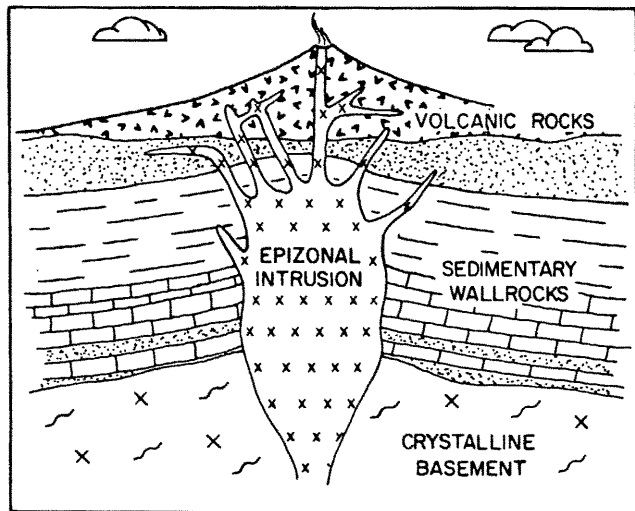


Figure 1. Vertical cross-section showing generalized geologic relations in the shallow intrusive environment of southwestern North America containing porphyry copper mineralization. The crystalline basement consists of Precambrian granite and metamorphic rocks. Sedimentary wallrocks comprise Paleozoic and/or Mesozoic clastic and carbonate rocks. Volcanic rocks are often cogenetic with the intrusion.

suggested two stages of fluid flow related to the development of porphyry copper deposits in this environment as shown schematically in Figure 2 (cf., Gustafson and Hunt, 1975; Gustafson, 1978). The first stage is characterized by circulation of magmatic fluids through a parent crystallizing magma or product igneous rock, concomitant with development of hypogene mineralization. The second stage, is termed "meteoric collapse", corresponds to the encroachment of meteoric fluids that produces late-stage argillic alteration. This convective circulation of meteoric waters through cooling plutons has been numerically predicted by several workers (eg., Norton and Knight, 1977; Cathles, 1977), but actual documentation of the presence of such fluids in fractured igneous rocks required application of stable isotope studies.

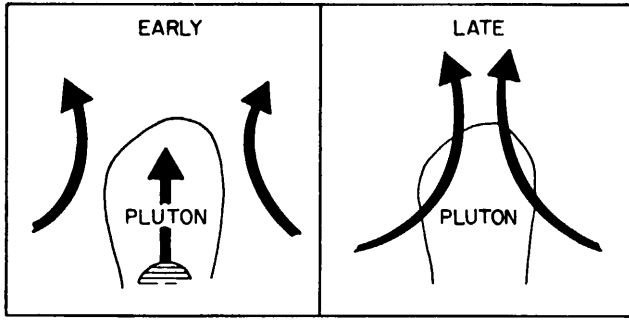


Figure 2. Vertical cross-section showing stages in the evolution of the hydrothermal systems forming porphyry copper deposits. Early fluids (left) are endogenous, with magmatic fluids traversing already-crystallized igneous rock and meteoric waters circulating in adjacent wall rocks. Late-stage "meteoric collapse" (right) consists of pervasive convection of meteoric waters. Arrows show fluid pathlines. The solid line in each figure encloses the cooling pluton; a small volume of melt remains at depth during early circulation.

Figure 3a shows published D/H and $^{18}O/^{16}O$ ratios of biotites and sericites from several porphyry copper deposits (Sheppard and others, 1969, 1971; Sheppard and Taylor, 1974). The stable isotope ratios of biotites from early alteration in numerous North American porphyry copper deposits are essentially the same regardless of geographic location. For example, compare values for biotites from Santa Rita, New Mexico, Ely, Nevada, Bingham, Utah, and Butte,

Montana, all of which fall within the range of igneous biotites (Taylor, 1974). In contrast, alteration sericites from Santa Rita, Ely, and Butte show systematic variation in hydrogen isotopes with geographic latitude. These variations are interpreted to reflect the formation of alteration sericites from meteoric waters.

The influx and gradual dominance of meteoric fluids flowing through igneous rocks during progressive hydrothermal alteration is recorded by systematic variations in the hydrogen and oxygen isotope ratios of selected minerals. Figure 3b shows the progressive variations in these ratios in biotite and sericite at the Butte, Montana deposit (Sheppard and Taylor, 1974). Among these data, igneous biotite occupies the apex, biotite from early dark micaceous alteration composes the variable hydrogen leg, and later sericitic (and argillic) alteration forms the variable-oxygen base of a crude inverted "L"-shaped pattern. This pattern resembles the characteristic variation in hydrogen and oxygen isotope ratios of biotite and feldspar in batholithic igneous rock undergoing increasing interaction with meteoric waters (Taylor, 1977). The inverted "L" pattern reflects the fact that igneous rocks are large reservoirs of oxygen, but contain only small amounts of hydrogen. The atomic oxygen to hydrogen ratios of igneous rocks are typically on the order of 500 or 1000:1, whereas for water the ratio is 8:1. As a result of this difference, when meteoric waters flow through and exchange with the igneous rock, it takes only a small amount of water to effect the rock's hydrogen isotope content. Large amounts of meteoric water are required, on the other hand, before the oxygen isotopes of the rock are effected because the rocks contain so much original igneous oxygen.

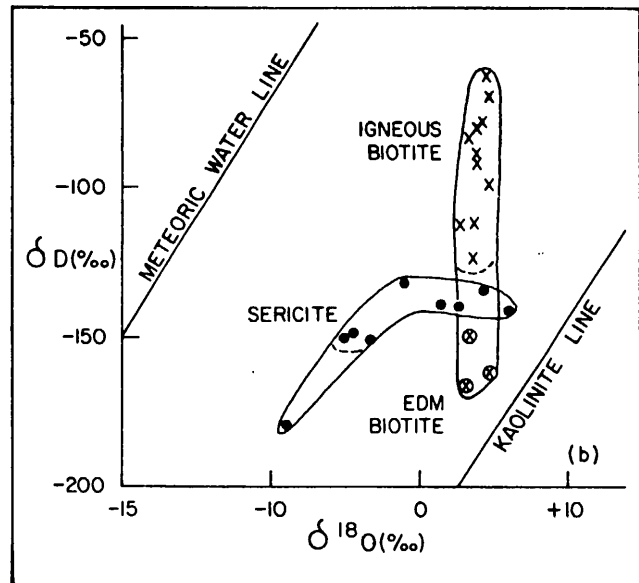
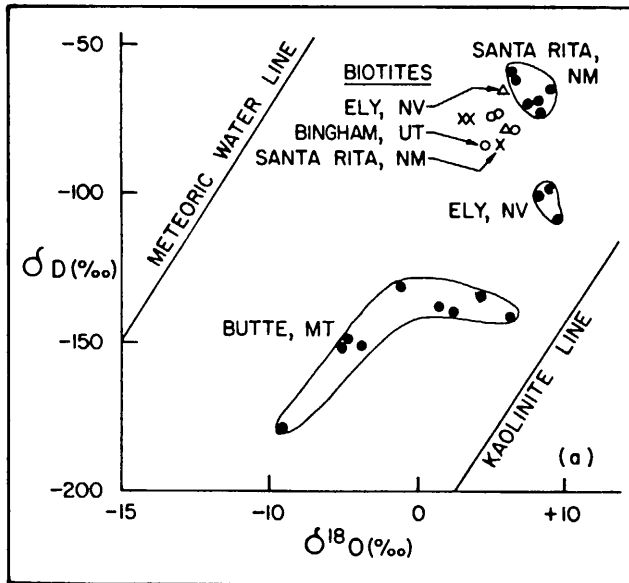


Figure 3. Hydrogen and oxygen isotope data for minerals from porphyry copper deposits (in parts per thousand relative to standard mean ocean water). (a) Biotites from Bingham, Utah (circles); Ely, Nevada (triangles); and Santa Rita, New Mexico (X's). Dots are sericites from Butte, Montana Main Stage alteration; Ely; and Santa Rita (Sheppard and others, 1971; Sheppard and Taylor, 1974). (b) Igneous biotite (X's), pre-Main Stage biotite from early dark micaceous (EDM) alteration (circles), and Main Stage sericite (dots) from Butte (Sheppard and Taylor, 1974).

MAGMATIC FLUIDS

Holland (1972) has pointed out that although several percent of dissolved H₂O are necessary to produce the amounts of hydrous phases (chiefly biotite and hornblende) seen in crystallized granodioritic rocks, chemical analyses typically reveal less than one weight percent H₂O in these igneous rocks (Nockolds, 1954). The conclusion is that the remaining magmatic H₂O originally present in the melts was exsolved during crystallization carrying with it the potential for forming hydrothermal ore deposits. Moreover, other workers have concluded that porphyry copper deposits were formed from magmatic fluids simply based on the spatial association of these mineralized systems with plutonic rocks.

The solubility of H₂O in granodioritic melts is directly related to pressure, but is essentially temperature-independent (Burnham, 1979). Dissolved H₂O can be released from a silicate melt in two ways. The first is the decrease from lithostatic to hydrostatic pressure on the magma as wall rocks are fractured during conductive heat transfer. The second is through early crystallization of anhydrous feldspar which causes H₂O to be concentrated in the remaining silicate liquid. When the H₂O content of the magma exceeds the saturation level for the prevailing pressure, an immiscible H₂O-rich fluid exsolves from the silicate melt. One result of this so-called "degassing" is a rapid crystallization of the silicate liquid surrounding the early feldspar phenocrysts, giving the igneous rocks a porphyritic texture. Also, because of the large volume increase resulting from H₂O exsolution at low confining pressures, there is a drastic release of mechanical energy which further fractures wall rocks and previously crystallized igneous rock (Burnham and Davis, 1971; Burnham and Ohmoto, 1980). The exsolution event will only cause quasi-plastic failure in igneous rocks at or slightly below the crystallization temperature, whereas magmas at temperatures well above the solidus are essentially unaffected. Diffusion of dissolved H₂O in magmas is slow, but exsolved bubbles of H₂O migrate rapidly through silicate liquid toward the top of the magma chamber, where development of a large low density bubble may lead to formation of collapse breccia pipes (Norton and Cathles, 1973). In crystalline portions of the igneous rock, exsolved fluids migrate through fracture networks generated by the strain-release associated with their exsolution.

The exsolved aqueous fluid is initially in chemical equilibrium with the crystallizing magma from which it was generated. If the temperature of the exsolved fluid does not decrease drastically below that of the parent magma, the fluid will precipitate a mineral assemblage comparable to the enclosing igneous rock, typically quartz, feldspar, biotite, and magnetite. This mineral assemblage will be

deposited in fractures formed in response to thermal effects in previously-consolidated igneous rock and in immediately adjacent wall rocks.

The chemical composition and temperatures of hydrothermal fluids can be approximated using inclusions trapped in structural defects of minerals. Magmatic fluid inclusions can be identified by their mode of occurrence and by experimentally-estimated temperatures of their formation. When these fluid inclusions are observed with high magnification at room temperature, a number of included solid phases are seen. These daughter minerals indicate that the magmatic fluids are typically highly saline, containing up to approximately 75 weight percent dissolved sodium and potassium chloride; thus, they are essentially hydrous saline melts (Roedder, 1971). Identification of such daughter minerals using the electron microprobe indicates that such magmatic fluids transported significant amounts of sodium, potassium, calcium, iron, copper, chloride, and sulfur. Notably low in the magmatic fluid is magnesium, which appears to be fixed in mafic minerals of igneous or hydrothermal origin (Anthony and others, 1983).

Experimental studies have shown that chloride in silicate melts is strongly partitioned into a coexisting H₂O-rich phase (Burnham, 1979; Kilinc and Burnham, 1972). However, the available partition coefficients and the chloride contents of granitic rocks (cf., Holland, 1972) both indicate that exsolved H₂O-rich magmatic fluids should have no more than 5 to 10 weight percent dissolved NaCl. Consequently, fluid inclusions that contain seven to ten times this amount of dissolved NaCl suggest that the hypersaline magmatic fluids have undergone some modification following original exsolution from the crystallizing magma. The most straight-forward mechanism for concentrating NaCl in fluids is by selective partitioning between aqueous liquid and vapor. If an initially low salinity liquid undergoes boiling, the salt content of the remaining liquid may be significantly elevated. Conversely, a low salinity vapor may undergo condensation to yield a small fraction of high salinity liquid. Either of these concentration processes require coexistence of liquid and vapor fractions, with the mass and volume fractions of the vapor portion being far greater than that of the liquid portion. Although the phenomena of boiling and condensation in porphyry copper deposits, as evidenced by fluid inclusions, have been discussed by Cunningham (1978), Henley and McNabb (1978), Nash (1976) and a number of other workers, much additional work remains to be done in order to completely understand their role in these systems.

THE METEORIC INCURSION

The steep temperature gradient imposed upon wall rocks by magmatic emplacement causes a proportionate lateral gradient in fluid density

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which in turn drives relatively dilute meteoric waters into convective motion through permeable wall rocks. High-temperature, lower-density fluids nearest the contact are displaced upward by cooler, denser fluids further away. Initial permeabilities of wall rocks vary significantly among different lithologies. These initial values are then either augmented or reduced through a variety of thermal and mechanical processes during pluton cooling (Knapp and Norton, 1981). Magma emplacement deforms and fractures the enclosing host rocks by mechanical effects. Additional fracturing of wall rocks is then caused by thermal expansion of pore fluids owing to heating by the adjacent intrusion (Knapp and Knight, 1977). Also, conductive heat transfer across the magma-wall rock contact causes additional fracturing in the rigid wall rock. Early fracturing of this latter type in host rocks is maximized in the region above the cooling pluton.

The pluton itself is initially molten and deforms plastically. Following emplacement, heat loss and magma crystallization proceed most rapidly in the roof of the cooling magma chamber. Volume decrease associated with the rapid cooling and crystallization causes extensive fracturing of this roof zone (Knapp and Norton, 1981). When magma crystallization is complete, the resulting igneous rock becomes susceptible to fracturing caused by thermal effects and devolatilization of uncrystallized magma. Permeabilities of plutons caused by cooling vary in location, orientation, and intensity with time. Detailed studies of mineralized plutons by Titley and coworkers (Titley and others, 1978; Haynes and Titley, 1980) show that although early fracturing occurs throughout the igneous rock mass following consolidation, there is a methodical retreat of fracturing toward the pluton contact with advancing time.

Fracturing incorporates the pluton into the permeable system through which magmatic and meteoric fluids circulate. When the crystallized pluton attains the large fracture-permeability of its enclosing wall rocks, broad-scale convective circulation cools the igneous rock with meteoric waters. The classic pattern of fluid convection in rocks of homogeneous permeability is depicted by Figure 4a. The broken arrow on Figure 4a shows early circulation in permeable wall rocks while the intrusion is still molten; the solid arrow corresponds to later fluid circulation when the crystalline stock is also permeable. Convective circulation around a cooling pluton leads to the distribution of isotherms shown schematically by Figure 4b (Norton and Knight, 1977; Cathles, 1977). The extended isotherm over the intrusion represents a broad zone of low vertical temperature gradient. The dotted extension of the low temperature contour shows the effects produced by a plumbing system which is confined above by low permeability.

In nature, flowlines vary depending on inhomogeneities in rock permeability and

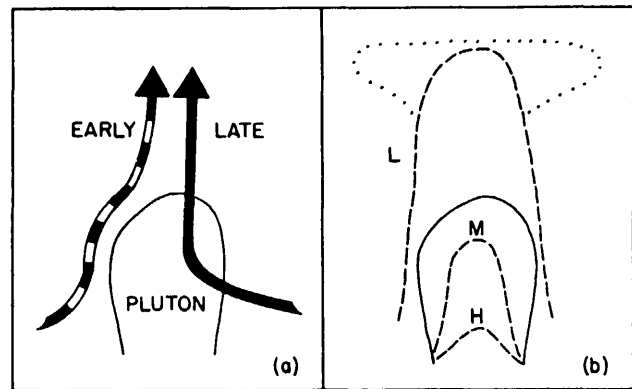


Figure 4. Positioning of fluid flow-lines (a) and isotherms (b) about a cooling pluton in uniformly permeable wall rocks. Flowlines, shown by arrows, are for early circulation (broken) when the central pluton is unfractured (impermeable), and later circulation (solid) when the stock becomes permeable through fracturing. Isotherms show relative positions for high (H), intermediate (M) and low (L) values. The dotted extension of the low isotherm depicts possible spreading as a result of sealing by an impermeable cap. The solid line in each figure encloses the cooling pluton.

differences in pluton geometry. Extensive fluid circulation during formation of porphyry copper deposits is evidenced by widespread isotopic exchange between minerals and hydrothermal fluids, and by wholesale chemical gains and losses in rocks (Norton, 1981). The changing position and abundance of flow permeability with time, coupled with the evolving temperature and composition of circulating fluids, is largely responsible for the zoning and paragenetic relations observed among alteration assemblages in porphyry copper deposits (Beane and Titley, 1982).

THE MAGMATIC-METEORIC TRANSITION

Fluid inclusions from porphyry copper deposits record the magmatic-meteoritic transition through systematic temporal variations in their temperature and salinity. A detailed record of this transition at the Santa Rita, New Mexico deposit has been compiled by Reynolds (1980). The earliest fluids to circulate in the Santa Rita stock had high salinities, up to 75 weight percent NaCl, and temperatures in excess of 750°C (Type IIIA, Figure 5a). The next generation of hydrothermal fluids was significantly cooler, having temperatures in the range 250-525°C (Type IIIB, Figure 5a); however, their salinities remained high. The temperatures and salinities of the second-stage fluids both decreased with progressing time. The 250° to 525°C homogenization temperatures of

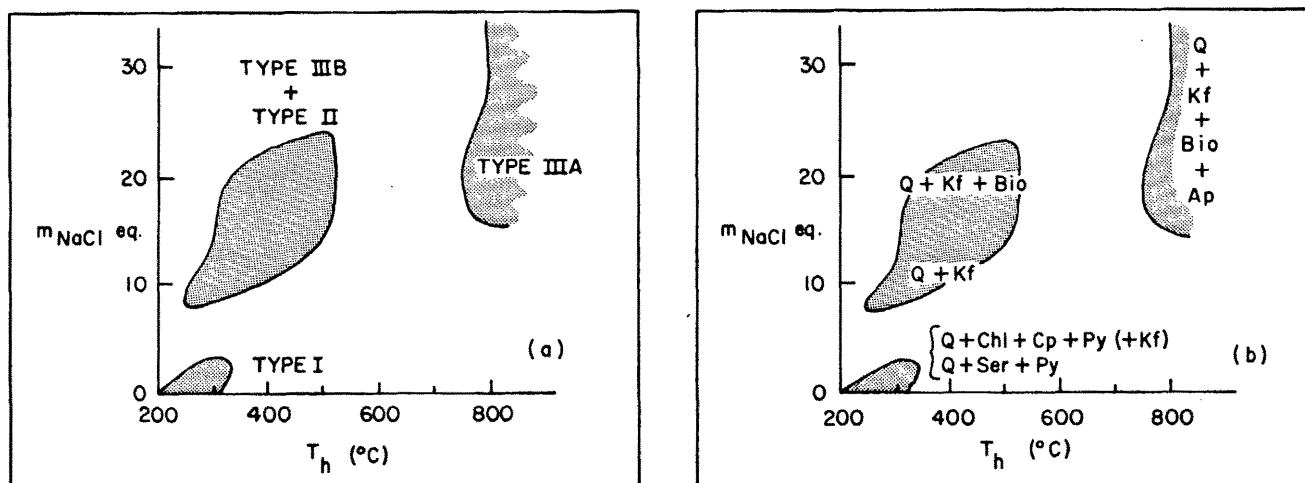


Figure 5. Thermal, salinity and alteration-mineral characteristics of different generations of hydrothermal fluids from the Santa Rita, NM porphyry copper deposit. (a) Measured homogenization temperatures (°C) and salinities (equivalent NaCl molality) of fluid inclusions. Type I = dilute, Type II = vapor-rich and Type III = hypersaline. (b) Mineral assemblages associated with each of the fluid types: Q = quartz, Kf = orthoclase, Bio = biotite, Ap = apatite, Chl = chlorite, Cp = chalcopyrite, Py = pyrite, Ser = sericite. From Reynolds and Beane (1983).

these fluid inclusions are characteristic of both liquid-rich and vapor-rich (Type II) varieties, indicating that the parent hydrothermal solutions were probably boiling. The third stage of hydrothermal fluids (Type I, Figure 5a) are characterized by significantly lower salinities, although their fluid inclusion homogenization temperatures are essentially the same as those of the immediately-preceding Type IIIB inclusions.

Walker (1979) has documented a comparable change in fluid properties in the breccia pipes at Copper Creek, Arizona, and various workers have shown all three fluid types to have been present in other porphyry copper systems (Nash, 1976; Eastoe, 1978; Wilson and others, 1980). The majority of fluid inclusion studies of porphyry copper deposits, however, have not recognized the high-temperature, high-salinity type, and only report the two later intermediate-temperature varieties.

Mineral assemblages formed by the various fluid types at Santa Rita are shown in Figure 5b. The mineral assemblage in the earliest veins, namely quartz, K-feldspar, and biotite, is consistent with fluids exsolved from a crystallizing granodioritic pluton. Sheppard and others (1971) have shown that the hydrothermal biotite at Santa Rita is isotopically comparable to igneous biotite as discussed above. Also, the oxygen isotope ratio of quartz accompanying the biotite is comparable to that of quartz in igneous rocks (Reynolds and Beane, 1983). The temperatures of the earliest generation of fluids are clearly magmatic. Thus, isotopic, fluid inclusion and mineralogical evidence all indicate that these early Type IIIA fluids are of magmatic origin. Oxygen isotope ratios of quartz and the vein-filling mineral assemblage in the second

high-salinity stage (Type IIIB, Figure 5a) are similar to the earlier Type IIIA fluids. These ratios suggest that the Type IIIB fluids were also originally exsolved from the pluton, but had cooled since generation at magmatic temperatures. The late Type I dilute fluids produced two alteration assemblages. The earliest, K-feldspar and chlorite with sulfides, formed the economic mineralization at the deposit; chlorite occurs as a deposited phase and as an alteration of earlier-formed biotite. This was followed by development of quartz-sericite-pyrite alteration. Stable isotope data indicate that this late sericite assemblage was formed from meteoric waters (Sheppard and others; 1969, 1971). The oxygen isotope ratio of quartz from the preceding chlorite-sulfide stage is comparable to that of the later quartz-sericite-pyrite assemblage (Reynolds and Beane, 1983). The fluid inclusion homogenization temperatures and salinities of these two stages are also comparable, providing further evidence that the fluids producing the chlorite-sulfide veins were derived from the same source as the fluids producing late quartz-sericite alteration, namely of meteoric origin. The K-feldspar + chlorite assemblage carrying sulfide mineralization is typically referred to as retrograde modification of early K-feldspar + biotite alteration, and the mineralization is credited to this supposed predecessor. Textural features, however, indicate that chalcopyrite deposition accompanied formation of hydrothermal chlorite.

Three mineralogically discrete alteration assemblages form at essentially the same temperature at Santa Rita as well as at some other porphyry copper deposits in southwestern North America (Beane and Tittley, 1981). Precipitation of the earliest assemblage,

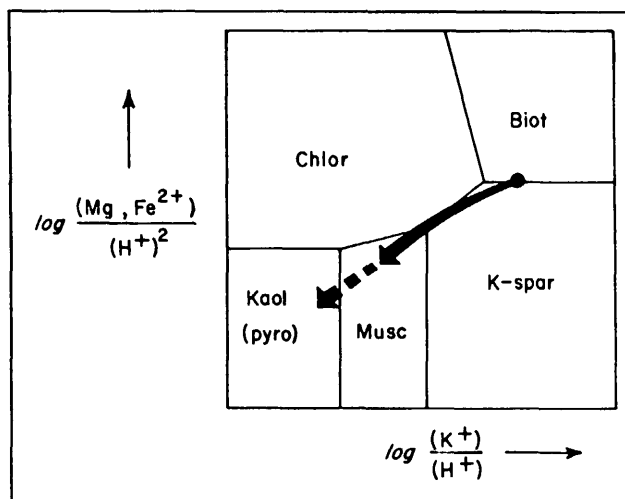


Figure 6. Schematic stability relations among silicate minerals in terms of ion-activity ratios in a co-existing aqueous phase. Phase relations are drawn based on observed mineral associations in porphyry copper deposits with formation temperatures near 350°C as determined using fluid inclusions. Alteration assemblages evolve as shown by the arrow. Mineral abbreviations: Biot(ite), Chlor(ite), Kaol(inite), Pyro(phyllite), Musc(ovite), and K-(feld)spar. From Beane and Titley (1981).

K-feldspar and biotite, is followed by K-feldspar plus chlorite deposition, and finally quartz and sericite are formed. The compositional evolution of a hydrothermal fluid required to precipitate these three assemblages at constant temperature is illustrated by the silicate-mineral stability diagram shown in Figure 6. This diagram depicts isothermal stability relations among K-feldspar, biotite, chlorite, muscovite (sericite), and kaolinite (or pyrophyllite) as a function of the ion activity ratios $(Mg^{2+})/(H^+)^2$ and $(K^+)/(H^+)$ in a coexisting aqueous fluid at quartz saturation. Although temperature is unspecified, the phase relations are consistent with vein assemblages observed in porphyry copper deposits which formed at temperatures in the range 300^o-400^oC (cf., Reynolds and Beane, 1983; Preece and Beane, 1982). The earliest K-feldspar + biotite assemblage was formed from high-salinity fluids, presumably of magmatic origin. This assemblage defines the starting point for successive reactions. When dilute fluids enter the system, as recorded by fluid inclusion salinities, the early minerals are progressively altered to K-feldspar plus chlorite and then to sericite as shown by the arrow in Figure 6. These later assemblages represent progressive reaction products as the meteoric fluids interact with, and eventually dominate, the original magmatic assemblage (Helgeson, 1970).

EVIDENCE OF FLUID CONVECTION

Detailed studies of time space relations among different kinds of fluid inclusions in porphyry copper deposits reveal systematic variations in properties of the trapped fluids. The occurrence of such variations in the fossil hydrothermal systems is predicted from theoretical concepts of fluid sourcelines and pathlines (Norton, 1978). A fluid sourceline connects the sequence of locations from which fluids flowing through some point of interest were derived. Several examples of sourcelines are shown in Figure 7a. Fluids flowing through

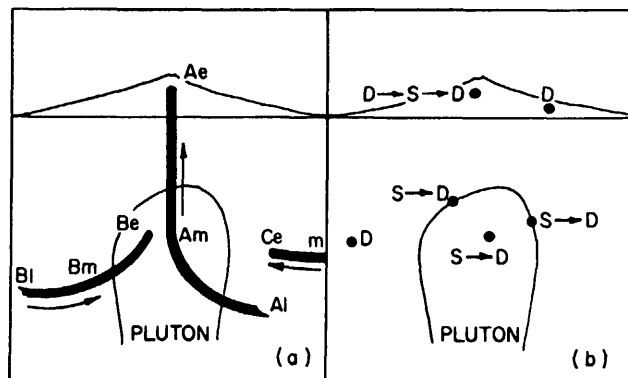


Figure 7. Vertical cross-section showing changes in sources and salinities of hydrothermal fluids with time in porphyry copper deposits. (a) Sourcelines A, B and C connect the sequence of sources of fluids which flow through these points at early (e), intermediate (m) and late (l) times. Arrows show fluid-flow pathlines. Modified from Norton (1978). (b) Order of occurrence of saline (S) and dilute (D) fluids with time, as indicated by the arrows, at different positions in the composite porphyry copper environment. From Beane and Titley (1981).

point B in a convecting system are drawn first from the area immediately surrounding that point (Be). As time progresses, the source location for fluids circulating through point B moves progressively further away from point Be outward into wallrocks (first Bm, then Bl), a directional trend nearly opposite to the fluid-flow pathlines shown by Figure 7a and the fluid flowlines discussed above. Thus the earliest fluids flowing through B are magmatic, while later-infiltrating fluids are meteoric. In contrast, early fluids that flow through rocks overlying the pluton are locally derived, hence meteoric in origin (Ae). As time progresses, high salinity magmatic fluids ascend to this point (Am). Still later, meteoric fluids that flowed from a wall rock source (Al) through the pluton, eventually circulate through this roof zone. Adjacent to the pluton, fluids circulate inward and upward, so magmatic fluids never reach point C.

Figure 7b shows time-space variations in fluid inclusion salinities that characterize several porphyry copper deposits (Beane and Titley, 1981). Assuming that magmatic fluids can be correlated with high-salinity fluid inclusions, and that meteoric fluids are indicated by the low-salinity variety, then the time-sequence of high- and low-salinity fluids at different positions in porphyry copper systems (Figure 7b) is consistent with the predicted evolution of fluid sourcelines in a convecting system (Figure 7a).

REVIEW

Thermal and compositional variations that characterize the transition from magmatic- to meteoric-dominated fluid flow during the cooling history of shallow plutons related to porphyry copper mineralization are traced schematically in Figure 8. Immediately following magma emplace-

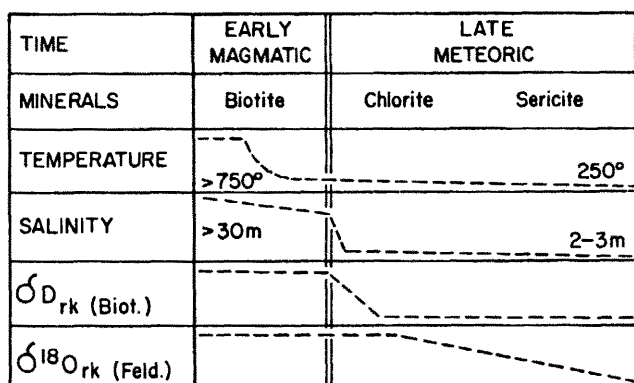


Figure 8. Variations in hydrothermal parameters during evolution of porphyry copper deposits. The double vertical line denotes the magmatic-meteoric transition. Fluid temperatures (°C) and salinities (equivalent NaCl molality) are determined from fluid inclusion studies. Decreases in hydrogen and oxygen isotope ratios are provisional based on concepts outlined by Taylor (1977) and measurements at Butte, Montana (Sheppard and Taylor, 1974).

ment, adjacent and overlying wall rocks are fractured while conductive heat transfer away from the still-molten magma causes convective flow of meteoric fluids through permeable wall rocks. This heat loss results in magma crystallization initially concentrated in the hood of the magma chamber. Once crystallized, the still-cooling igneous rock is itself fractured by thermal contraction.

Crystallization of the magma concentrates dissolved H₂O in the remaining melt until it reaches the saturation level, at which time an immiscible H₂O-rich phase, "magmatic water", is violently exsolved causing fracturing of already-crystallized igneous rock and wall rocks. The exsolved magmatic fluid concentrates chloride

from the magma, and with it base metals which form stable complexes. Trapped inclusions of these fluids, recognized by near-magmatic homogenization temperatures, have high salinities and can be called hydrous saline melts. Although the manner in which these high salinities are obtained is uncertain, they do exist. The logical explanation is salt partitioning, either through boiling or condensation, but fluid inclusion evidence for these phenomena is sometimes lacking. The magmatic fluids circulating through newly crystallized igneous rock produce a "granitic" vein assemblage of quartz, K-feldspar, biotite, and magnetite. The vein-forming minerals exhibit an oxygen isotope signature indicative of their magmatic heritage.

When the pluton has completely crystallized, generation of magmatic fluids ceases. Fracturing from violent exsolution is finished, but the effects of continued thermal contraction persist. Lateral thermal and fluid-density gradients through the fractured pluton-wall rock system cause widespread convective fluid flow centered on the intrusion. The convective circulation introduces lower-salinity meteoric fluids into the cooling pluton. The earliest indicators of the meteoric incursion, as seen in Figure 8, are: 1) a significant decrease in fluid salinity as recorded by fluid inclusions, 2) a shift in the hydrogen isotope composition of potassic-altered rocks, and 3) chloritization of earlier-formed biotite. This incursion is not marked by drastic temperature decrease, because fluid inclusion data indicate that magmatic fluids have cooled to temperatures on the order of 300°-400°C before the meteoric influx. Neither do oxygen isotopes provide a contemporaneous indicator, because relatively large amounts of meteoric fluid are required to exchange with igneous rocks before their magmatic isotopic signature can be changed.

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