

Copper deposition by fluid cooling in intrusion-centered systems: New insights from the Bingham porphyry ore deposit, Utah

P.B. Redmond

M.T. Einaudi

E.E. Inan

M.R. Landtwing

C.A. Heinrich

Department of Geological and Environmental Sciences, Stanford University, Stanford, California 94305, USA

Isotope Geology and Mineral Resources, Department of Earth Sciences, ETH Zürich, Switzerland

ABSTRACT

Quartz veins in porphyry copper deposits record the physiochemical evolution of fluids in subvolcanic magmatic-hydrothermal systems. We have combined cathodoluminescence (CL) petrography with fluid-inclusion microthermometry to unravel the growth history of individual quartz veins and to link this history to copper ore formation at Bingham, Utah. Early barren quartz veins with K-feldspar + biotite (potassic) alteration selvages occur throughout the 2 km vertical exposure of quartz monzonite porphyry stock. At depths of 500 m to at least 1350 m below the orebody, fluid inclusions in these barren veins trapped a single-phase CO₂-bearing fluid containing ~2–12 wt% NaCl_{equiv}. Within and to depths of 500 m below the orebody, early quartz veins contain abundant hypersaline liquid (38–50 wt% NaCl_{equiv}) and vapor-rich inclusions trapped together at temperatures of 560–350 °C and pressures of 550–140 bar, consistent with fluctuations between lithostatic and hydrostatic pressure at paleodepths of 1.4 to 2.1 km. CL petrography shows that bornite and chalcopyrite were deposited together with a later generation of quartz and K-feldspar in microscopic fractures and dissolution vugs in early barren quartz veins and wall rock. This late quartz contains hypersaline liquid (36–46 wt% NaCl_{equiv}) and vapor-rich inclusions trapped at 380–330 °C and at 160–120 bar hydrostatic pressure. We conclude that a single-phase magmatic-hydrothermal fluid underwent phase separation to hypersaline liquid (or brine) and vapor ~500 m below the base of the orebody at a paleodepth of ~2.5 km. Brine and vapor continued to ascend and formed multiple generations of barren quartz veins with potassic selvages. Thermal decline to temperatures below 400 °C was the main driving force for copper-iron sulfide deposition, given the lack of evidence of mixing of brines with low-salinity waters, the lack of correspondence of the ore zone with the initiation of phase separation, and no change in wall-rock alteration style.

Keywords: Bingham Canyon, porphyry copper, fluid inclusions, cathodoluminescence.

INTRODUCTION

Porphyry-hosted ore deposits, our main source of copper, provide us with a three-dimensional view of upper-crustal magmatic-hydrothermal systems above large calc-alkaline plutons. Much of what is known about the complex physical and chemical evolution of magmatic-hydrothermal fluids between the deep plutonic regime of granitoid intrusions and the fumarolic emanations observed in active volcanoes comes from the study of fluid inclusions in veins from porphyry-hosted ore deposits (Roedder, 1971; Ulrich et al., 2002). These observations, and supporting experimental and isotopic data, show that saline magmatic-hydrothermal fluids undergo a complex history involving separation of a high-temperature magmatic volatile phase into two fluids, a hypersaline liquid coexisting with a vapor phase across a wide pressure-temperature (*P-T*) range (Henley and McNabb, 1978; Burnham, 1979; Dilles, 1987; Hedenquist and Lowenstern, 1994). Metal sul-

fides may precipitate from these ascending fluids because of fluid cooling, the chemical effects of phase separation, interaction with wall rocks, or mixing of magmatic fluids with meteoric water (Gustafson and Hunt, 1975; Reynolds and Beane, 1985; Hemley and Hunt, 1992; Hedenquist et al., 1998). The relative importance of these different processes in generating economic orebodies has been the subject of much debate.

Identifying the dominant ore-forming process within these complex systems is extremely challenging because of the difficulty in establishing the temporal relationships between the formation of quartz-hosted fluid inclusions and the deposition of copper sulfides. Traditional fluid-inclusion studies invariably record a broad range of *P-T* conditions and fluid compositions within individual quartz veins. For example, previous studies of vein quartz from the porphyry orebody at Bingham, Utah, identified coexisting hypersaline liquid and vapor-rich inclusions that constrain copper de-

position to a *P-T* range of 725–303 °C and 1120–620 bar (Roedder, 1971; Moore and Nash, 1974; Bowman et al., 1987). Cathodoluminescence (CL) petrography, previously applied to vein formation in porphyry deposits (Penniston-Dorland, 2001; Rusk and Reed, 2002), was used in the present study to differentiate successive generations of fluid inclusions within the large *P-T* range recorded by previous workers and to identify the fluid inclusions most closely related in time to copper ore formation. Further, we have used fluid inclusions to track the *P-T-X* evolution of magmatic fluids over a 2 km vertical interval to define the paleodepth at which a single-phase fluid separated into a hypersaline liquid and vapor well below the orebody. Together, these data identify for the first time a clear relationship between the evolution of deep magmatic fluids and the formation of an overlying porphyry copper orebody.

METHODS

Our sequence of quartz veins is based on six months of mapping and drill-core logging at the mine. We examined 75 polished thin sections and 180 fluid-inclusion plates to assess the spatial and temporal variability of quartz-hosted fluid inclusions: 25 fluid-inclusion plates were examined using a CL detector mounted on a JEOL 6300 scanning electron microscope. Microthermometric data were collected on fluid-inclusion assemblages (FIAs) as defined by Goldstein and Reynolds (1994) by using a Fluid Inc. adapted U.S. Geological Survey gas-flow heating and freezing stage and a THMSG 600 Linkam conductive stage. Measurements were carried out on four quartz vein samples (41 FIAs) from the high-grade (>0.7 wt% Cu) orebody in the quartz monzonite porphyry (QMP) and on three barren quartz vein samples (11 FIAs) from the same host rock 1200–1350 m below the orebody.

DEPOSIT GEOLOGY

The Bingham deposit is centered on a composite late Eocene porphyry stock intruded into late Eocene monzonite and Pennsylvanian sedimentary rocks (Lanier et al., 1978). Our study focused on the main stage of copper de-

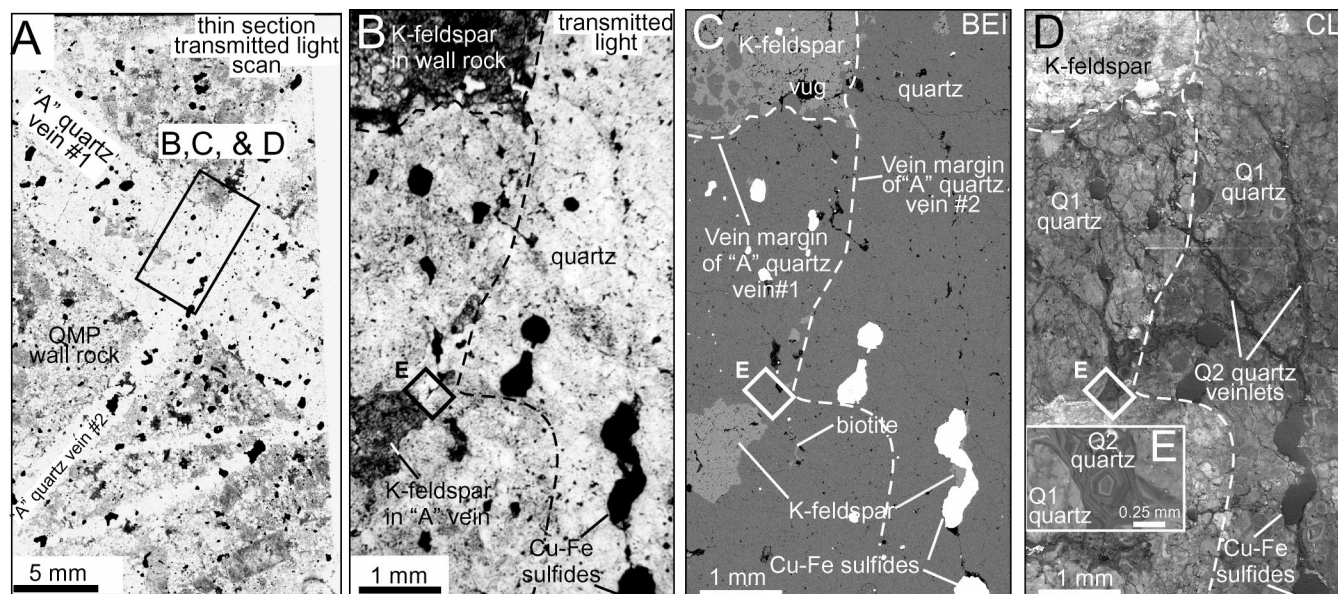


Figure 1. A: Thin section overview showing early Q1 quartz vein cut and offset by second Q1 quartz vein. QMP is quartz monzonite porphyry. Labeled boxes show location of images B, C, D, and E. B: Transmitted-light photomicrograph showing intersection of Q1 quartz veins. C: Backscattered-electron image (BEI) of same area as B. D: Cathodoluminescence (CL) image of same area as in B and C, showing dark-luminescing Q2 quartz veinlets containing copper-iron sulfide grains; Q2 veinlets cut more brightly luminescing Q1 quartz. E: CL image of growth zones in Q2 quartz.

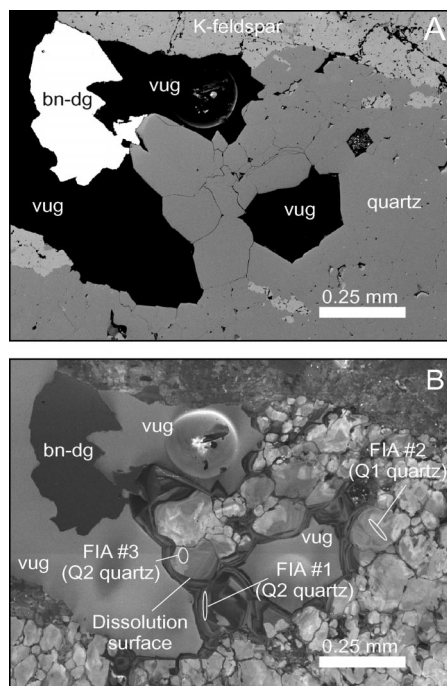


Figure 2. A: Backscattered-electron image of vug in Q1 quartz vein in high-grade quartz monzonite porphyry (2.9 wt% Cu). B: Cathodoluminescence image of dissolution vug in Q1 quartz lined with Q2 quartz and overgrown by bornite-digenite (bn-dg) grain. Same field of view as A. Locations of measured fluid-inclusion assemblages (FIA) are shown.

position associated with intrusion of the earliest porphyry, QMP, which contains the most abundant quartz veins and the highest-grade copper ore. This ore consists of digenite + bornite + chalcopryite, but no pyrite, and is associated with hydrothermal K-feldspar + biotite. Vein truncation relationships coupled with abrupt decreases in copper grades and potassic alteration intensity at the contact between QMP and other volumetrically minor porphyries indicate that these later intrusive-hydrothermal events did not contribute significant copper to the deposit (Redmond, 2002). Light stable isotope studies indicate that the hydrothermal fluids responsible for sulfide deposition and potassic alteration were magmatic in origin (Sheppard et al., 1969, 1971; Bowman et al., 1987). Quartz + molybdenite and pyrite + sericite veins postdate all porphyries (Redmond, 2002), consistent with the Re-Os results of Chesley and Ruiz (1997). These veins are not considered here.

EARLY BARREN QUARTZ VEINS CUT BY QUARTZ + SULFIDE VEINLETS

QMP contains abundant 0.5–2-cm-wide quartz veins, with potassic alteration halos, throughout the 2 km of open-pit and drill-core exposure. These veins contain vitreous, granular quartz and minor K-feldspar and biotite. Within the orebody they also contain bornite, digenite, and chalcopryite. Crosscutting relationships show that these quartz veins evolved through time from short, irregular veins to throughgoing, straight-walled veins (Redmond, 2002). The quartz in these veins is

dominantly composed of interlocking anhedral, 0.1–5 mm grains of moderate- to bright-luminescing quartz with irregular CL zonation. This quartz is referred to as Q1 quartz (Fig. 1).

CL petrography led to the discovery that these apparently simple quartz veins and the adjacent QMP wall rock throughout the orebody are cut and overprinted by 0.25–0.5-mm-wide fractures that cannot be seen in hand samples or by standard transmitted-light microscopy. These fractures are filled with a distinct dark-luminescing quartz generation, termed Q2 quartz (Figs. 1 and 2), that is accompanied by copper-iron sulfides and minor K-feldspar. Abundant, irregular 0.1–2 mm vugs, connected by Q2 ± sulfide veinlets, are partly or completely filled with grains of chalcopryite, bornite, and Q2 quartz displaying well-developed CL growth zonation (Figs. 1E and 2B). Vug margins and Q2 quartz overgrowths commonly truncate growth zones in earlier Q1 quartz grains, indicating that vug formation involved quartz dissolution (Fig. 2). These Q2 quartz + sulfide veinlets and Q2 quartz-lined vugs contain the majority of the copper-iron sulfides in the QMP orebody.

The overall abundance of macroscopic quartz veins does not change significantly downward from the base of the orebody (Fig. 3). However, CL petrography of samples from below the orebody revealed only rare Q2 quartz + sulfide veinlets.

FLUID-INCLUSION RESULTS

Within the QMP orebody, the fact that both Q1 and Q2 quartz contain abundant halite-

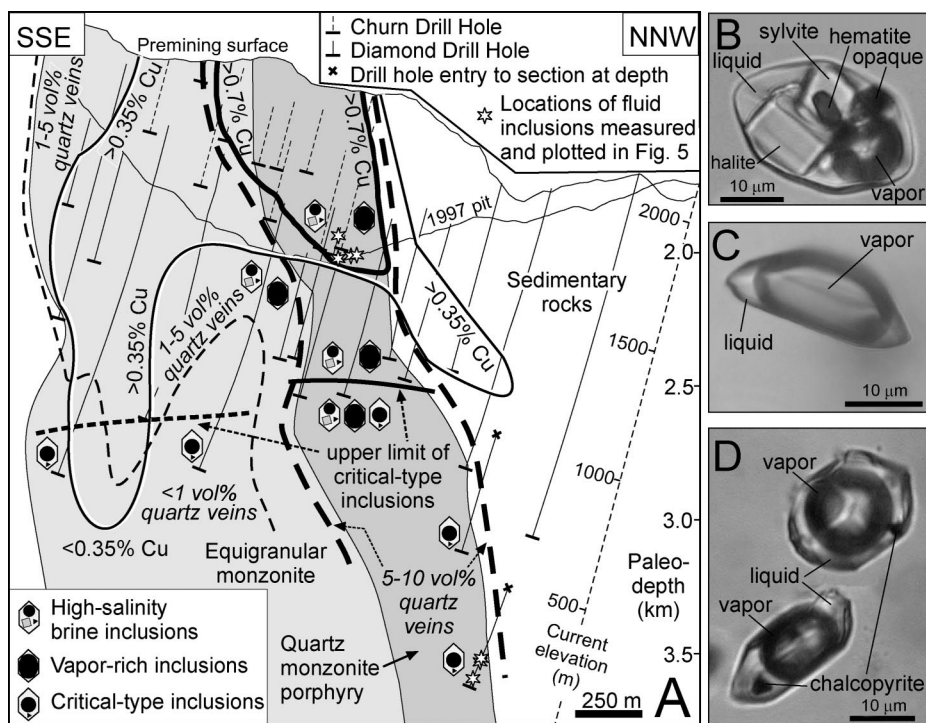


Figure 3. A: Geologic cross section through Bingham copper deposit showing contours of 0.35 and 0.7 wt% Cu grade, quartz vein abundance, and upper limit of critical-type fluid inclusions; bold 0.7% contour defines high-grade quartz monzonite porphyry orebody. Section is rotated 15° to west to reverse post-ore Basin-and-Range tilting. Photomicrographs are of (B) brine inclusion from orebody, (C) vapor-rich inclusion from orebody, and (D) critical-type inclusions from 1200 m below orebody.

saturated liquid-rich inclusions (Fig. 3B) and vapor-rich inclusions (Fig. 3C) indicates that hydrothermal fluids were boiling throughout the period from early quartz vein formation through to Cu-Fe-sulfide deposition. Brine inclusions in Q1 quartz in 4 quartz veins spanning a 96 m vertical interval in the orebody (Fig. 3) have an average homogenization temperature (T_h) of 457 °C (range 350–560 °C) and a salinity of 44 (range 38–50) wt% NaCl_{equiv} (Fig. 4) and were trapped at pressures of 550–140 bar (Fig. 5), consistent with fluctuations between lithostatic and hydrostatic pressure conditions at 1.4–2.1 km paleodepth. Petrographically similar brine inclusions in Q2 quartz in the same 4 veins have a significantly lower average T_h value of 367 °C (range 330–380 °C), but only a slightly lower average salinity of 40 (range 38–45) wt% NaCl_{equiv} (Fig. 4). Pressure estimates of 160–120 bar (Fig. 5) are consistent with hydrostatic conditions at 1.2–1.6 km paleodepth (Fig. 5). We estimate pressure by using the data from the NaCl-H₂O system (Sourirajan and Kennedy, 1962; Bodnar and Vityk, 1994) combined with the observation that brine inclusions were trapped in the presence of vapor.

Fluid inclusions in Q1 quartz in quartz veins from 500 to 1350 m below the orebody (Fig. 3) are dominated by intermediate-density, CO₂-bearing fluid inclusions that display

“pseudocritical behavior” (Bodnar, 1995) during heating. These critical-type inclusions consist of liquid and vapor at room temperature (Fig. 3D) and commonly contain a small opaque daughter (probably chalcopyrite). Halite-saturated liquid-rich inclusions and vapor-rich inclusions are extremely rare in deep veins. Critical-type inclusions from 1200 to 1350 m below the orebody (3.5 km paleodepth based on their position relative to the orebody samples) have a T_h range of 430–350 °C (Fig. 4). Sufficient CO₂ is present in the critical-type fluid inclusions to form visible clathrate that dissolves between 6.0 and 8.6 °C (for all but one FIA), but not enough to saturate a liquid CO₂ phase, yielding maximum salinity estimates of 2–7 wt% NaCl_{equiv} (based on Diamond, 1992). These inclusions formed at 3.5 km paleodepth; if we assume that lithostatic pressure (910 bar) prevailed during their formation, then the trapping temperatures for a 5 wt% NaCl solution would have been 470–590 °C, according to Bodnar and Vityk (1994).

DISCUSSION AND CONCLUSIONS

We have defined an upper limit of CO₂-rich, critical-type fluid inclusions that is located 500 m below the base of the QMP orebody and have shown that halite-saturated brine and coeval vapor-rich inclusions predominate at higher elevations. On the basis of this spatial

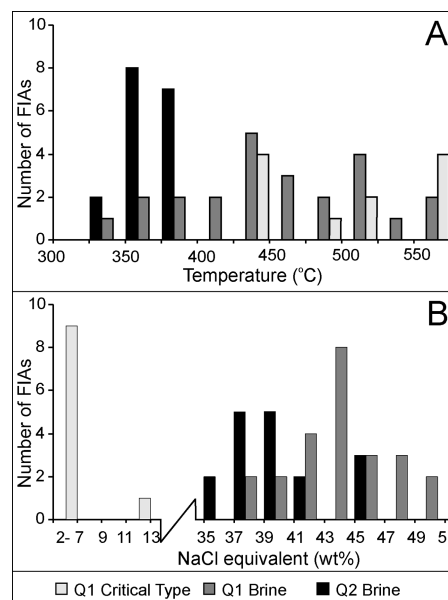


Figure 4. A: Histogram of fluid-inclusion homogenization temperatures and estimated trapping temperatures (in case of critical-type inclusions). Most fluid-inclusion assemblages (FIA) are homogenized by vapor-bubble disappearance, and few are homogenized by halite dissolution. **B:** Histogram of estimated salinities for same inclusion assemblages.

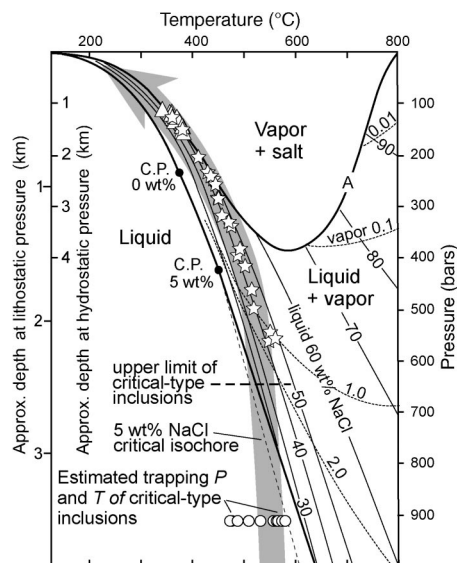


Figure 5. Pressure-temperature (P - T) diagram for NaCl-H₂O system (Fournier, 1999) showing fluid-inclusion microthermometric data and inferred P - T trajectory (gray arrow) of magmatic hydrothermal fluids leading to ore formation at Bingham. White circles—critical-type inclusions in Q1 quartz. White stars—brine inclusions in Q1 quartz in four samples from quartz monzonite porphyry orebody. White triangles—brine inclusions in Q2 quartz coeval with ore from same four samples. Sample locations are shown in Figure 3. Curve A shows three-phase (vapor + liquid + salt) boundary for system NaCl-H₂O. C.P. is critical point.

distribution and microthermometric analysis, we propose a P - T - X path for ascending magmatic-hydrothermal fluids that explains both populations of fluid inclusions and leads to copper ore formation during the QMP-related magmatic-hydrothermal event (Fig. 5). Low-salinity, single-phase fluids carrying significant amounts of copper (based on preliminary laser-ablation inductively coupled plasma-mass spectrometry analysis) (Landtwing et al., 2002) exsolved and ascended from a source magma chamber well below our deepest exposure. Fluid temperatures declined ~ 50 °C over the lithostatic depth interval from 3.5 to 2.5 km, suggesting that the P - T trajectory of these supercritical fluids was close to an adiabatic path. Near-isothermal decompression of supercritical fluids to 2.5 km paleodepth led to increased ore metal solubility (Hemley and Hunt, 1992) but declining quartz solubility (Fournier, 1999), and hence to the formation of barren quartz veins.

Ascending supercritical fluid intersected its solvus (Fig. 5) at 550–500 °C and 700–600 bar and underwent separation to a hypersaline liquid and a vapor phase at ~ 2.5 km paleodepth. Brine and vapor continued to ascend, forming Q1 quartz veins, but precipitating little or no sulfide as they cooled to ~ 400 °C. Pressure estimates of 550–140 bar for vapor-saturated brines at 550–400 °C and ~ 2 km paleodepth indicate that the fluids that deposited Q1 quartz fluctuated between lithostatic and hydrostatic pressure during cooling, consistent with data from active geothermal systems and rock mechanics (Fournier, 1999). The bulk of the copper-iron sulfides in the QMP orebody was deposited with later Q2 quartz in veinlets and vugs, as the temperature declined to 380–330 °C at hydrostatic pressure (~ 160 – 120 bar). Dissolution surfaces between Q1 and Q2 quartz (Fig. 2) are likely due to fluids cooling in the P - T region of retrograde quartz solubility (Fournier, 1999), as proposed by Rusk and Reed (2002) to explain similar CL textures in vein quartz from Butte, Montana.

Sulfide deposition in magmatic-hydrothermal systems may be controlled by a number of physical and chemical processes, as outlined here. At Bingham, we see no change in the style of wall-rock alteration associated with the pre-ore and syn-ore vein evolution stages. The zone where phase separation began is 500 m below the base of orebody. The salinity of brine inclusions in Q2 quartz is similar to that of brine inclusions in Q1 quartz. These three observations suggest that water-rock interaction, phase separation, or mixing of magmatic fluids with lower-salinity meteoric waters were not the dominant factors driving ore-

grade sulfide deposition. We conclude that fluid cooling to below 400 °C, during the late Q2 quartz deposition in equilibrium with K-feldspar + biotite, was the dominant process that led to sulfide saturation and the formation of the high-grade porphyry orebody at Bingham. Fluid temperature within the QMP generation of quartz veins decreased with time at any one sample location, as the overall system cooled below the ductile to brittle transition, while magmatic fluids continued to flow upward and outward on the larger scale. Our observations also imply that the orebody cooled well below 400 °C after the main magmatic-hydrothermal event associated with the QMP emplacement; it was only locally reheated by subsequent minor magmatic-hydrothermal events, followed by the formation of the final quartz + molybdenite and pyrite + sericite veins.

ACKNOWLEDGMENTS

We thank Kennecott Utah Copper and Kennecott Exploration for access to the mine and for partly funding this study. Jim Reynolds provided invaluable guidance on fluid inclusions.

REFERENCES CITED

- Bodnar, R.J., 1995, Fluid-inclusion evidence for a magmatic source for metals in porphyry copper deposits, in Thompson, J.F.H., ed., *Magmas, fluids and ore deposits: Mineralogical Association of Canada Short Course Series*, v. 23, p. 139–152.
- Bodnar, R.J., and Vityk, M.O., 1994, Interpretation of microthermometric data for H_2O -NaCl fluid inclusions, in De Vivo, B., and Frezzotti, M.L., eds., *Fluid inclusions in minerals: Methods and applications*: Blacksburg, Virginia, Virginia Tech, p. 117–130.
- Bowman, J.R., Parry, W.T., Kropp, W.T., and Krueger, S.A., 1987, Chemical and isotopic evolution of hydrothermal solutions at Bingham, Utah: *Economic Geology*, v. 82, p. 395–428.
- Burnham, C.W., 1979, *Magmas and hydrothermal fluids*, in Barnes, H.L., ed., *Geochemistry of hydrothermal ore deposits* (second edition): New York, John Wiley and Sons, p. 71–136.
- Chesley, J.T., and Ruiz, J., 1997, Preliminary Re-Os dating of molybdenite mineralization from the Bingham Canyon porphyry copper deposit, Utah: *Society of Economic Geologists Guidebook Series*, v. 29, p. 165–170.
- Diamond, L.W., 1992, Stability of CO_2 clathrate hydrate + CO_2 liquid + CO_2 vapour + aqueous KCl-NaCl solutions—Experimental determination and application to salinity estimates of fluid inclusions: *Geochimica et Cosmochimica Acta*, v. 56, p. 273–280.
- Dilles, J.H., 1987, Petrology of the Yerington batholith, Nevada: Evidence for evolution of porphyry copper ore fluids: *Economic Geology*, v. 82, p. 1750–1789.
- Fournier, R.O., 1999, Hydrothermal processes related to movement of fluid from plastic into brittle rock in the magmatic-epithermal environment: *Economic Geology*, v. 94, p. 1193–1211.
- Goldstein, R.H., and Reynolds, T.J., 1994, *Systematics of fluid inclusions in diagenetic minerals*: Tulsa, Oklahoma, Society for Sedimentary Geology Short Course 31, 199 p.
- Gustafson, L.B., and Hunt, J.P., 1975, The porphyry

- copper deposit at El Salvador, Chile: *Economic Geology*, v. 70, p. 857–912.
- Hedenquist, J.W., and Lowenstern, J.B., 1994, The role of magmas in the formation of hydrothermal ore deposits: *Nature*, v. 370, p. 519–527.
- Hedenquist, J.W., Arribas, A., Jr., and Reynolds, T.J., 1998, Evolution of an intrusion-centered hydrothermal system: Far Southeast-Lepanto porphyry and epithermal Cu-Au deposits, Philippines: *Economic Geology*, v. 93, p. 373–404.
- Hemley, J.J., and Hunt, J.P., 1992, Hydrothermal ore-forming processes in the light of studies in rock-buffered systems: II. Some general geologic applications: *Economic Geology*, v. 87, p. 23–43.
- Henley, R.W., and McNabb, A., 1978, Magmatic vapor plumes and ground-water interaction in porphyry copper emplacement: *Economic Geology*, v. 73, p. 1–20.
- Landtwing, M.R., Heinrich, C.A., Halter, W.E., Pettker, T., Redmond, P.B., and Einaudi, M.T., 2002, Fluid evolution at the Bingham Cu-Au-Mo-Ag porphyry deposit: *Geochimica et Cosmochimica Acta*, v. 66, p. A430.
- Lanier, G., John, E.C., Swensen, A.J., Reid, J., Bard, C.E., Caddey, S.W., Wilson, J.C., and Moore, W.J., 1978, General geology of the Bingham mine, Bingham Canyon, Utah: *Economic Geology*, v. 73, p. 1228–1241.
- Moore, W.J., and Nash, J.T., 1974, Alteration and fluid inclusion studies of the porphyry copper ore body at Bingham, Utah: *Economic Geology*, v. 69, p. 631–645.
- Penniston-Dorland, S.C., 2001, Illumination of vein quartz textures in a porphyry copper ore deposit using scanned cathodoluminescence: Grasberg Igneous Complex, Irian Jaya, Indonesia: *American Mineralogist*, v. 86, p. 652–666.
- Redmond, P.B., 2002, Magmatic-hydrothermal fluids and copper-gold ore formation at Bingham Canyon, Utah [Ph.D. thesis]: Stanford, California, Stanford University, 228 p.
- Reynolds, T.J., and Beane, R.E., 1985, Evolution of hydrothermal fluid characteristics at the Santa Rita, New Mexico, porphyry copper deposit: *Economic Geology*, v. 80, p. 1328–1347.
- Roedder, E., 1971, Fluid inclusion studies on the porphyry-type ore deposits at Bingham, Utah, Butte, Montana, and Climax, Colorado: *Economic Geology*, v. 66, p. 98–118.
- Rusk, B., and Reed, M., 2002, Scanning electron microscope-cathodoluminescence analysis of quartz reveals complex growth histories in veins from the Butte porphyry copper deposit, Montana: *Geology*, v. 30, p. 727–730.
- Sheppard, S.M.F., Nielsen, R.L., and Taylor, H.P.J., 1969, Oxygen and hydrogen isotope ratios of clay minerals from porphyry copper deposits: *Economic Geology*, v. 64, p. 755–777.
- Sheppard, S.M.F., Nielsen, R.L., and Taylor, H.P., Jr., 1971, Hydrogen and oxygen isotope ratios in minerals from porphyry copper deposits: *Economic Geology*, v. 66, p. 515–542.
- Sourirajan, S., and Kennedy, G.C., 1962, The system H_2O -HCl at elevated temperatures and pressures: *American Journal of Science*, v. 260, p. 115–141.
- Ulrich, T., Günther, D., and Heinrich, C.A., 2002, The evolution of a porphyry Cu-Au deposit, based on LA-ICP-MS analysis of fluid inclusions: Bajo de la Alumbrera, Argentina: *Economic Geology*, v. 97, p. 1888–1920.

Manuscript received 2 July 2003

Revised manuscript received 1 November 2003

Manuscript accepted 12 November 2003

Printed in USA