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Fluid Inclusion Evidence for Magmatic-Hydrothermal Fluid Evolution in the Porphyry Copper-Molybdenum Deposit at Butte, Montana

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Abstract

The porphyry Cu-Mo deposit in Butte, Montana, formed where magmatic hydrothermal fluids, introduced with injections of porphyritic dikes, fractured and permeated the Butte Quartz Monzonite. These fluids formed a stockwork of quartz and quartz-sulfide veinlets with a variety of styles of potassic and sericitic alteration envelopes. The distribution of vein and alteration types and the distribution of fluid inclusions in these veins record the progressive pressure, temperature, and compositional evolution of the hydrothermal fluids that formed this world-class deposit.

Deep drilling and 1,300 m of offset along the Continental fault provide a vertical view of almost 3 km through the Butte deposit. Deep veins within and below the highest Mo grades are quartz dominated with thin K-feldspar or, less commonly, biotitic alteration rims. Fluid inclusions in deep veins trapped a single phase aqueous fluid containing 2 to 5 wt percent NaCl equiv and 2 to 8 mol percent CO₂ at temperatures between 575° and 650°C and pressures between 200 and 250 MPa, corresponding to depths between 6 and 9 km. Although Cu grades are low in this region, abundant chalcopyrite daughter minerals in fluid inclusions indicate that the fluids were Cu rich. Fluids that formed these veins transported Cu from the magma below, upward into the region of Cu mineralization with only minor Cu precipitation.

Over a kilometer above the bulk of deep quartz and quartz-molybdenite veins, the highest Cu grades are in and around chalcopyrite-bearing quartz-sulfide veins with biotitic alteration (early dark micaceous veins), and their upward, equivalent magnetite-chalcopyrite-pyrite-quartz veins with wide K-feldspar, green sericite, and chlorite alteration (pale-green sericitic veins). These veins contain more evidence for brine-vapor unmixing than any other vein type. The upward progression of early dark micaceous veins to pale-green sericitic veins formed where low salinity, CO₂-bearing fluids, similar to those trapped in deep quartz veins, ascended, depressurized, sometimes unmixed, and cooled from ~650°C at 90 MPa to ~475°C at ~50 MPa.

As low salinity, CO₂-bearing, aqueous fluids, similar in composition to fluids trapped in deep quartz veins, cooled at shallow depths, they formed late pyrite-quartz veins with sericitic alteration. These veins formed from fluid cooling at temperatures between 370° and 450°C at transiently hydrostatic pressures between 40 and 70 MPa, corresponding to depths of 4 to 7 km. Most pyrite-quartz veins formed at pressures and temperatures above the H₂O-NaCl-CO₂ solvus, but evidence for brine-vapor unmixing is also present. Pyrite-quartz veins formed at progressively greater depths as the hydrothermal system cooled, overprinting much previous mineralization.

Late Cu-Pb-Zn-Ag-As-rich Main stage veins formed from dilute fluids containing <3 wt percent NaCl equiv and <2 mol percent CO₂. These fluids were trapped between 230° and 400°C under hydrostatic pressures between 20 and 60 MPa and depths of 2 to 6 km. No evidence of boiling is observed in Main stage veins.

Fluid inclusion phase relationships indicate that the Butte porphyry Cu-Mo deposit formed at 5 to 9 km depth, greater than any other porphyry-type deposit. At Butte, the similarity in bulk composition of fluids trapped in early quartz-rich veins with potassic alteration and late pyrite-quartz veins with sericitic alteration implies that an underlying magma continually provided low salinity, CO₂-bearing fluids of relatively constant composition during the entire life of the hydrothermal system. We hypothesize that rather than resulting from changes in fluid chemistry due to magma crystallization, the entire suite of vein and alteration types and the ore metal distribution reflect the path of cooling, depressurization, and wall-rock interaction of a parental magmatic-derived fluid of relatively constant initial composition.

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Fluid inclusions, vein and alteration relations, and ore metal distribution indicate that Cu and Mo were introduced into the hydrothermal system by the same fluids, but that the mechanisms of precipitation of these metals were decoupled. Early dark micaceous and, to a greater extent, pale-green sericitic, veins have wide alteration envelopes and contain more evidence for fluid unmixing than any other vein type, which suggests that chalcopyrite precipitation was driven by a combination of fluid unmixing, fluid-rock reaction, and fluid cooling between 650° and 475°C. Most molybdenite mineralization, however, is in quartz-dominated veins with little or no alteration that are dominated by low salinity inclusions. These veins formed in response to pressure decrease rather than cooling. After chalcopyrite and molybdenite precipitation, low salinity fluids cooled, usually at temperatures and pressures above the H₂O-NaCl-CO₂ solvus, to produce significant acid and voluminous sericitic alteration accompanied by pyrite-quartz vein formation that overprints much of the deposit and contains anomalous but noneconomic Cu.