Dynamic P-T-X evolution of saline fluids in ore-forming magmatic-hydrothermal systems

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Introduction. The subsurface hydrology of fluid flow in and above upper-crustal magmatic intrusions controls the formation of major ore-deposit types on land and on the seafloor, including Sn-W veins, porphyry-Cu-Mo-Au deposits, epithermal Au-Ag deposits, and volcanic-hosted polymetallic massive sulphide deposits. In most instances, fluids from multiple sources interact with each other, including magmatic fluids, meteoric water and/or seawater. In all magmatic-hydrothermal environments, fluid processes involve phase separation into variably saline brines and vapour-like fluids. These physical processes, notably fluid mixing and fluid phase separation, have profound chemical effects for metal transport and selective mineral precipitation (Heinrich 2006, 2007). Fluid evolution paths through P-T-X space are not steady-state but evolve dynamically as a result of heat transfer by the flowing fluids themselves. Understanding the scale and efficiency of ore formation requires that we quantify these dynamic feedbacks between physical and chemical processes of fluid – rock interaction, using a combination of observational and modeling tools (Heinrich et al. 2005).

Combining field and lab observation with numeric modeling. Careful geological and geophysical mapping at the scale of orebodies and their geological context allows 3-dimensional reconstruction of the geometry of ore-forming magmatic-hydrothermal systems, including the delineation of metal zonations and the architecture of volcanic edifices and subjacent magma chambers. Field observations also allow reconstruction of the sequence of magma emplacement (lava flows, dykes and intrusions) in relation to multiple events of veining and hydrothermal alteration, providing a relative temporal framework of interacting magma and fluid evolution (e.g., Halter et al. 2004). Based on such field relationships, it is also possible to radiometrically date the absolute timing of events, although analytical precision limits the resolution of the commonly rather short-lived magmatic-hydrothermal processes. Once a good geological framework is established in space and relative timing, petrographic study of fluid inclusion assemblages and subsequent microthermometric and microchemical analysis can provide quantitative information about pressure, temperature, phase-state (single or two-phase) and the chemical composition of the fluids. However, such data is naturally selective and defines at best a ‘snapshot’ picture of local fluid processes, for selected locations and short time periods within the overall hydrothermal evolution of the system. Numerical process simulation based on basic physics and chemical thermodynamics allows linking this incomplete geological record, to obtain an integrated model for the large-scale dynamic process (Matthai et al. 2007; Kostova et al. 2004).

First results and tentative conclusions. First applications of this combined observational and modeling approach to understand porphyry-type and related epithermal ore systems indicates that large-scale fluid transport leading to ore formation does not primarily depend on the specific geometry and permeability distribution of each individual geological system. To a first order, ore-forming efficiency is dominated by the inherent physical and chemical properties of the fluids, together with a small number of system-scale geological parameters (Driesner and Geiger 2007). These include the gross permeability, the size and depth of magma chambers determining the magnitude of fluid and heat sources, and first-order topographic effects such as the presence or absence of a volcanic edifice or an overlying seawater column. A new quantitative description of the phase-relations and properties of fluids in the binary NaCl – H2O system, applicable from ambient conditions to deep magma chambers and from pure water to pure salt (Driesner 2007; Driesner and Heinrich 2007), provides a good approximation to explain the behaviour of...
magmatic-hydrothermal systems involving interactions between variably saline single- and two-phase fluids.

Recent geological and fluid-inclusion studies of the Bingham Canyon porphyry-Cu-Mo-Au deposit (Landwing et al. 2005 and in prep.), the El Teniente Cu-Mo deposit (Klemm et al. 2007) and the Questa porphyry-Mo deposit (Klemm et al. 2008) were carried out along with initial generic modeling studies of saline fluid flow (Geiger et al. 2005; Driesner and Geiger 2007) and thermodynamic reaction calculations (Heinrich 2005). Although still preliminary, the combination of results provide a new but consistent picture of fluid processes forming rich ore deposits of geologically related origin, but different metal endowment. Laser-Ablation ICPMS analysis showed that low-density vapour is a highly efficient ore fluid at high temperature, provided that it has an adequate water density to hydrate metal complexes at elevated pressure (Williams-Jones and Heinrich 2005).

**Vapour, brine, and metal ratios of ore deposits.** The final metal endowment of large magmatic-hydrothermal ore deposits is controlled by a combination of magmatic source processes generating primary fluids of different metal content, subsequent element segregation by fluid phase separation, and selective precipitation of ore minerals from different fluids at temperatures below ~420°C (Heinrich et al. 2005; Audétat et al. 2008). Quantitative fluid-inclusion and modeling results consistently indicate that low-salinity magmatic vapour and derived aqueous liquids are probably the dominant Cu and Au mineralizing fluids in most porphyry as well as epithermal ore systems. The hypersaline liquid (brine) formed by high-temperature condensation is volumetrically minor, and probably plays a rather subordinate role in Cu and Au enrichment. Only the Cu-poor molybdenum porphyries such as Questa and other Climax-type Mo deposits, and also Sn-W veins as indicated by earlier studies, are dominantly formed from the residual hypersaline liquid (Klemm et al. 2008). This brine tends to remain close to the roof of upper-crustal intrusions, due to its higher density and viscosity, whereas the more abundant Cu ± Au rich vapour ascends due to its lower density and viscosity (Geiger and Driesner 2007). Selective transport of gold to epithermal temperatures is optimised by a fluid flow path allowing a relatively low-salinity vapour rich in volatile sulphur to separate from a minor quantity of hypersaline liquid at depth (>400 bar, >400°C). The vapour then leaves the two-phase coexistence surface, cooling and ascending iso-compositionally in the single-phase stability field. It is an inherent feature of the NaCl – H₂O and similar salt – water fluid systems, that such a fluid cooling path can cross at elevated pressure above the critical curve of the system, thereby allowing the vapour to continuously ‘contract’ to an aqueous liquid of identical composition (Heinrich et al. 2004). Application of experimental solubility data to multicomponent reaction models indicates that this physical process of vapour contraction favours a chemical fluid evolution permitting very high concentrations of Au to be transported down to temperatures as low as 200°C, where high-grade epithermal gold deposits can be formed very efficiently (Heinrich 2005). The same process probably also affects the Cu/Au ratio of porphyry-style ore deposits: rapid expansion of fluids in shallow porphyries favours complete co-precipitation of both Cu and Au, whereas cooling of vapour-derived ore fluids at greater depth favours selective deposition of Cu only (± Mo) in porphyry ores and the physical separation of Au, which may then be available for the generation of overlying epithermal gold deposits.

**References:**
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