Invitation

2018 SEG Distinguished Lecturer

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Fluid evolution and selective metal enrichment in magmatic-hydrothermal Cu-Au ore systems

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Porphyry Cu-Au systems result from a chain of processes at different spatial and time scales, from lithosphere interaction generating large ore provinces to the precipitation of minerals in distinct vein types. This talk will summarise recent research on physical modelling of magma chamber dynamics and high-precision geochronology and discuss how the pressure - temperature path of ascending fluids controls the efficiency of ore deposition and the metal ratios of the deposits. Although research progress was based on the development of sophisticated microanalytical tools and modelling methods, we can now apply its results using rather simple observations like fluid inclusion petrography.

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Magmatic-hydrothermal ore formation, including porphyry and epithermal deposits, results from a chain of processes including (1) early lithosphere preparation; (2) magma generation in the upper mantle and lower crust; (3) magma ascent and fluid saturation; (4) fluid expulsion from magma and focused fluid flow; (5) fluid cooling, expansion and phase separation; (6) ore mineral precipitation and hydrothermal alteration; and (7) eventual erosion to exposure and possible supergene enrichment. All members of this chain are equally essential, and a well-organized connection along the process chain determines whether ore formation is successful and where the largest and richest deposits are found. Metal enrichment requires an optimal use of energy and is the opposite of chaotic, which disperses chemical components. Thermal and chemical gradients between the Earth's interior and its surface drive ore formation, and the dissipation of thermal gradients at different spatial scales determines the efficiency and the characteristic time scales of the contributing processes.

Mineral provinces require specific plate-scale processes occurring at plate-tectonic time scales (> 10 Ma) or longer. For example, the subduction pre-history of the lithosphere may prepare the Cu/Au ratio of residual dispersed sulfide available for subsequent extraction by partial melting. Province-scale processes also determine changing stress states of magmatically active lithosphere, with compression favoring periods of lower-crustal magma fractionation and buildup of a non-erupting upper-crustal magma chamber. Ratios of lithophile trace-element in igneous rocks (e.g., Sr/Y) monitor the evolution of fertile hydrous magmas by lower-crustal fractionation. Uplift and erosion also occur at plate-tectonic time scales, potentially causing supergene enrichment across chemical gradients towards the oxygenated hydrosphere.

Deposit size or total metal tonnage is determined foremost by the volume of hydrous magma able to deliver a sustained flux of fluid. For this step, a large rapidly-filled upper-crustal magma chamber is better suited than an extensive network of smaller reservoirs, which are probably more typical for intermittently active but non-mineralizing volcanoes. The duration of filling and crystallization of large upper-crustal magma chambers is a few million years at most, as indicated by the spread of individual zircon ages resolved by high-precision thermal ionization geochronology. The duration of fluid extraction, punctuated by one or several events of porphyry emplacement above the magma chamber, occurs during a fraction of the life time of the magma chamber. Efficient fluid collection is confined to the period during which major parts of the magma chamber are in a state of a high-crystallinity mush. Numerical modeling shows that this intermediate stage of crystallization permits rapid tube-flow of magmatic fluids, typically over a few hundred thousand years at most. It leads to fluid focusing towards the highest cupolas in the roof of the magma chamber, from where porphyries and vein networks originate. Mapping the size

and the top surface of upper-crustal magma chambers should be a high priority in exploring for new porphyry deposits under cover.

Deposit composition, including ore grade and metal ratios, is dominated by the two greatest metal enrichment steps in the process chain: the efficiency of metal extraction by hydrous fluid from residual melt in the magma chamber and the efficiency of ore mineral precipitation from this fluid. Metal extraction together with sulfur is optimized by a moderately saline single-phase fluid of intermediate density: fluid properties that promote chloride complexation and hydration of metals at magmatic temperatures. Sulfur extraction together with the metals allows subsequent precipitation of Cu-Fe-sulfides, which is driven by fluid decompression and cooling. Magmatic fluid decompression and sharp temperature gradients at the interface to convecting meteoric water yield optimal conditions for co-precipitation of Au with Cu-Fe-sulfides, leading to high-grade Cu-Au ore shells that characterize porphyry deposits formed 2-4 km below paleosurface. Expansion of high-temperature magmatic vapor towards shallow fumaroles suppresses Cu-Fe-sulfide precipitation due to reduced sulfide activity and may lead to porphyry Au deposits formed in presence of solid halite or a dry salt melt. Fluid cooling at greater depth than the Cu-Au optimum selectively precipitates Cu-Fe-sulfides ± molybdenite, whereas Au may partition into H_2S-rich vapor. This deep low-salinity vapor can subsequently cool and contract towards an epithermal aqueous liquid, to form Au-only deposits by low-pressure boiling, reduction or mixing with meteoric water. Different density - salinity - temperature paths therefore control mineral precipitation efficiency and the variety of ore deposits in porphyry systems. Our current understanding of the depth- and pressure dependence of selective metal precipitation has been derived from microanalysis of fluid inclusions and sophisticated lab experiments, but the decisive fluid parameters — i.e., phase state and density of fluids — can be assessed by simple fluid inclusion petrography during early stages of exploration.