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Geologic Complexity in Fluid-Flow Models for Ore-Forming Hydrothermal Systems

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Introduction

Numeric simulations are rapidly developing into a critical tool for predicting the behaviour of fluid flow systems, with applications in the use of groundwater, hydrocarbons and geothermal energy. In such active systems, measured hydraulic parameters are commonly available to support increasingly realistic numeric models. Fluid flow in the deeper parts of the earth is inaccessible to hydraulic measurements, and the fluids have long escaped from older systems exposed by later uplift and erosion. Although we have no precise information about the driving forces and rates of past fluid flow, the magnitude of the resulting chemical mass transfer is well known in some cases. In particular, hydrothermal ore deposits provide some of the most spectacular evidence of advective mass transfer and of the scales of fluid flow, from crustal systems to individual mineralised veins. With the rapid advances in finite-element algorithms and computational hardware, the question about the 'useful' level of geologic detail in simulations becomes relevant. Will geologically realistic finite-element simulations eventually advance our understanding of hydrothermal mass transfer processes, to the level of true predictive power for ultimate application in mineral exploration? Or should numeric simulations focus on generic representation of fundamental processes, in light of the incomplete constraints in specific paleo-hydrothermal systems?

Application to the Mount Isa copper deposit

We are developing the object-oriented finite-element software CSP to explore these questions using several test cases. In the metasediment-hosted copper deposit at Mount Isa, mass-transfer is particularly well quantified at the mine scale, and also at the scale of a large late-metamorphic flow system that includes the likely source region of the fluids and ore metals. Geology and geochemical tracers suggest regional-scale hydrothermal copper advection from oxidised metabasalts toward their contact with dolomitic metasediments. Here, an oxidised Cu-rich brine reacted with reduced metadolomite, in which pre-existing sedimentary pyrite provided a geochemical trap for the precipitation of chalcopyrite ($CuFeS_2$). This geologically well-supported process seemed to be in conflict with careful mass-balance measurements at the mine-scale that demonstrates a major addition of S in excess of the pre-existing mass of sulphur in the ore body volume. The Mount Isa copper deposit is located on the foot wall of a steep reverse fault, which offsets metamorphic grade by about 200ºC. Flow simulations were motivated by the hypothesis that uplift of the hotter block creates a thermal fluid updraft in the footwall metasediments hosting the deposit. A basal heat flow of $45mW/m^2$, constant brine salinity, a permeability distribution based on surface and mine mapping and a seismic transect, and reverse fault motion at a rate of 0.2 to 6cm/year are assumed. The CSP simulations predict a robust evolution of flow patterns following the onset of fault slip. Early on, several small eddies develop in the highly permeable brecciated ore body. As the thermal perturbation spreads laterally, small convection cells form in the variably permeable metasediments and eventually coalesce into 10-kilometre scale cells passing through the metabasalts. Eddy convection thus mixes chemically contrasting fluids entering the ore body volume from the large-scale circulations through the two rock reservoirs, explaining copper deposition in agreement with all geochemical constraints.

General implications

The formation of a hydrothermal ore deposit requires a large fluid flux, a high degree of focussing, and a chemical contrast for dissolution and re-precipitation of the metals. The requirement of focussed flow through a small deposition site commonly stands in competition with the need for a chemical driving force for effective ore-mineral precipitation. Fluid mixing is inherently favorable for high-grade ore deposition, compared with direct fluid/rock reaction where the final ore grade is always limited by mass-balance constraints. The simulations of the Mount Isa system illustrate how chemical gradients between major rock reservoirs can provide a driving force for trace-element enrichment within a crustal-scale hydrothermal system, while concurrent smaller-scale fluid circulations provide an effective mechanism of mineral precipitation by mixing of fluids with contrasting provenance. The two scales of fluid flow are a direct consequence of the geometric complexity of permeability distribution, indicating that prudent incorporation of geological detail in the simulations may be decisive in understanding and ultimately predicting the formation of major ore deposits.

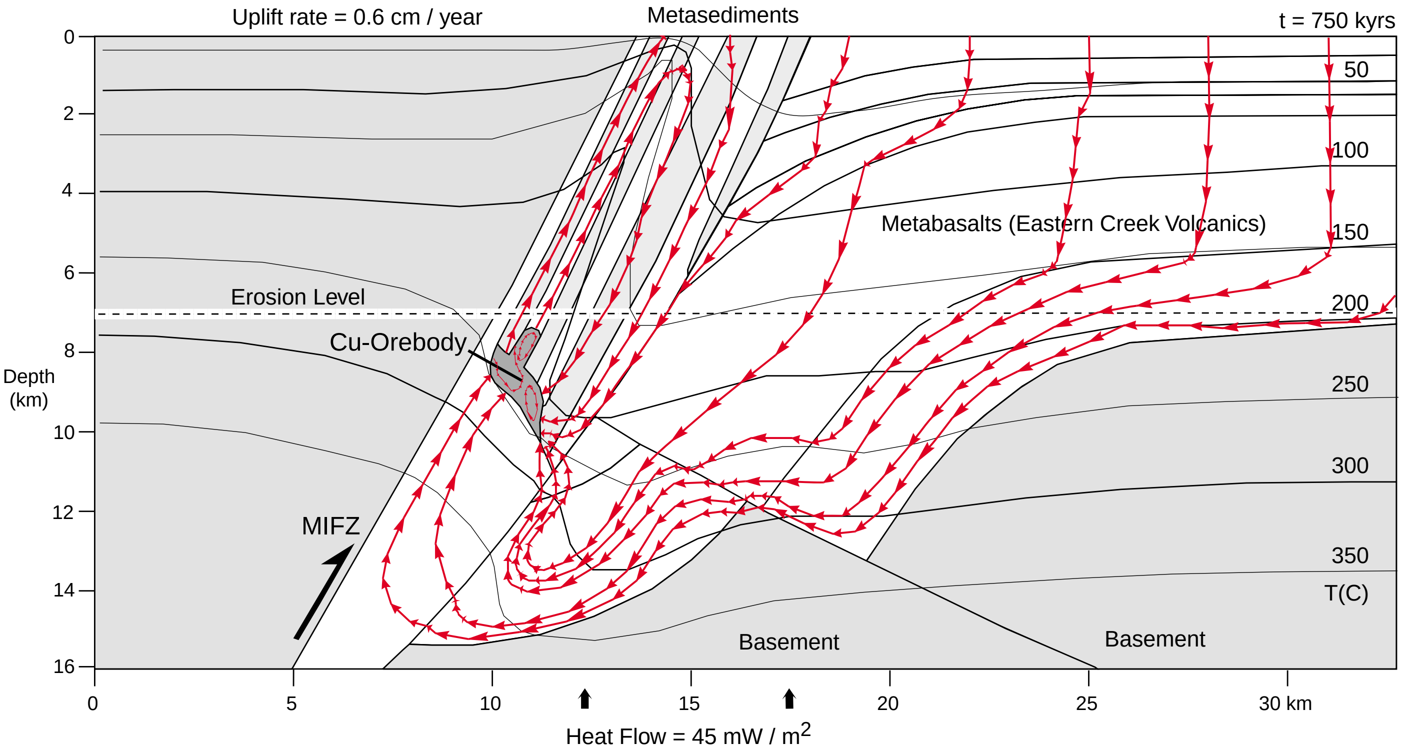

Figure 1: Geometry of rock units and predicted flow pattern in the late-metamorphic fluid system associated with copper mineralisation at Mount Isa (Australia)