

## Time scales and length scales in magmatic mineral systems

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Mineral systems are the product of multi-scale interactions of physical and chemical processes. In attributing a particular effect to a proximal cause, both must be operating at similar length and time scales, and the fastest process at any given scale will dominate in a competition for heat, mass and momentum. Magmatic ore formation involves a range of processes that operate from the scale of LIP-forming mantle plumes to grain-scale processes within the magma or country rock. Disposition of these processes on the length-time scale plot is controlled by four different properties: chemical and thermal diffusivity, and magma and crust/mantle viscosity. We use this principle to evaluate a number of common assumptions about magmatic ore forming processes.

Magmatic Ni sulfide systems require a source of S from country rocks, and a number of mechanisms have been proposed, including volatile transport from pyrite breakdown in thermal aureoles, diffusion of liberated S through country rock, and direct incorporation and subsequent melting of sulfide-bearing xenoliths. Following the scaling principle, direct melting of xenoliths is by far the fastest process, falling on the overlap between the magma viscosity and thermal diffusivity control domains. Consequently it is a slower process than the flow of the carrier magma, which falls entirely within the magma viscosity domain. Hence, it is likely that sulfidic xenoliths are liable to be transported some distance from their site of incorporation before they have time to melt and release all of their sulfides as molten sulfide liquid. A consequence of this is that much of the mass transfer of assimilated sulfide in magmas may be in the form of partially molten and disaggregated xenoliths, rather than purely as suspended droplets. This may account for the very common close association between sulfide accumulations and xenoliths in many mafic-intrusion-hosted deposits.

Subsequent enrichment of the sulfide liquid depends on processes of chemical diffusion in the magma. The critical controls are the diffusivities of chalcophile elements in silicate magma (slow), and the thickness and stability of compositional boundary layers developed around suspended droplets, in relation to the rates of transport and accumulation of sulfide liquid to form ore-grade accumulations (fast). Equilibration times for typically sized sulfide droplets undergoing Stokes settling in a basaltic magma are of the order of 10s-100s of days. Unless flow is turbulent, causing rapid breakdown of boundary layers, sulfide droplets would need to be transported on a scale of km from their source in order to attain high R factors. Sulfide droplets could be transported considerable distances in sulfide-undersaturated magmas; the role of sulfide liquid solubility in the formation of Ni-Cu ores has been greatly overestimated.

Even at very rough levels of estimation, it is possible to use scaling analysis to draw some fundamental and in some cases counter-intuitive conclusions about ore forming processes. It is necessary to challenge some long-established pieces of received wisdom: particularly, the assumption that ore forming processes operate at equilibrium. Kinetics play a much larger role than is commonly allowed for.