Geophysical Research Abstracts
Vol. 17, EGU2015-15802, 2015
EGU General Assembly 2015

Numerical simulation of structural evolution from regional to local scale in the Outokumpu ore district, eastern Finland

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Numerical simulations of geological processes may be used in several ways. On the one hand there is an analytical, or forensic approach, analogous to geophysical inversion, to constrain boundary conditions and to demonstrate how a particular geological process or sequence of events is feasible, or even probable. Alternatively, or additionally, modeling of earth processes can be used in a predictive sense, where forward modeling of various scenarios representing different initial states and applied boundary conditions and processes can provide generic or specific insights – depending on model complexity – which may be applied to problems as diverse as geohazard risk assessment and mineral exploration. These two approaches are complementary, and either may be emphasized, depending on the degree of understanding or density of data in a given study area.
Here we review how the results of modeling can be used to develop and test structural scenarios and hypotheses and how they can be integrated with new data sets, in this case, deep crustal and upper crustal high resolution reflection seismic data acquired in recent years in the Paleoproterozoic Outokumpu ore district in eastern Finland.
A range of process models have been devised and run for the Outokumpu mineral system, including coupled convective reactive transport models, coupled thermomechanical models assessing thermal regimes in rifting, and coupled mechanical and fluid flow models, but here we focus on the results of mechanical modeling using the finite element code FLAC.
Models designed at different scales have provided simple and plausible solutions that affirm the geometric and kinematic scenarios based on regional and mine-scale structural data. At regional scale, FLAC models effectively simulated the partitioning of deformation into NW-SE trending ductile shear zones and domains where coeval folding and thrusting have NE-trending axial trends. At a more detailed district scale, development of local duplexing during folding of lithologically and mechanically diverse layered sequences – the serpentinites of the Outokumpu assemblage and the enclosing metaturbidites - was demonstrated in the FLAC simulations. The overall geometry is very reminiscent of dilational zones in ramp-flat imbricate fault systems that facilitate orogenic gold mineralization. At Outokumpu however, there is no evidence for hydrothermal transport of copper during regional metamorphism and deformation, yet the overall tabular form of the deposit demands significant structural mobilization. Hence, the system may be regarded as closed during peak metamorphic conditions, with essentially local remobilization and redistribution of components, possibly locally facilitated by decarbonation and dehydration reactions within altered metaperidotite lenses. Although we also simulated permeability structures and local fluid pathways in and around lenticular bodies – serpentinite proxies – that were both stronger and weaker than enclosing rock units, it must be admitted that there are few experimental or theoretically calculated constraints on rock behavior under such conditions. Thus, there are some earth environments and process that still elude our modeling capacity, with respect to thermodynamics and rheological behavior, in particular, the role of diffusion and mechanical behaviour of rocks dominated by quartz-sulfide mineralogy, subjected to amphibolites facies conditions for tens of millions of years.