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From crystal lattice to field scale – Using diffusion modelling to constrain time scales of metamorphic processes: An example from the Granulite Massif, Germany

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Mass transport in the crust and upper mantle is an important, kinetically controlled process in the solid Earth that operates over a variety of length and timescales, ranging from nanometers to kilometers and days to millions of years. Fluid flow, diffusion and mineral reactions are the major processes governing the transport of mass and heat and thus quantitative knowledge of mechanisms and rates and the parameters controlling these processes is crucial. In this contribution, it is shown how the temperature dependence of element exchange between co-existing minerals is typically used to constrain metamorphic temperatures. Experimental strategies are presented to derive relevant properties and the results are discussed in the light of interpreting the so-called diffusive closure temperature in minerals. In order to demonstrate the implications of the kinetic effect, experimentally derived Fe-Mg interdiffusion data for garnet and clinopyroxene are used to model the evolving mineral zoning of these minerals during exhumation and cooling of a mantle xenolith from the Granulitgebirge, Germany. The rock contains remarkable exsolution textures from former megacrysts that produced up to mm-wide, alternating lamellae of garnet (grt) and clinopyroxene (cpx). Compositional profiles of major and trace elements measured with the electron microprobe perpendicular to the grt-cpx interfaces reveal systematic zoning patterns for Fe, Mg, Al, Si, Cr, Ti in cpx and Ca, Fe, Mg, Mn in grt. It is shown that zoning patterns such as Fe-Mg exchange between grt and cpx can be used to extract cooling rates and thus timescales of exhumation, while other profiles, such as Cr, and Ti can be rather related to the growth history of the lamellae. Furthermore, zoning profiles in the lamellae can only be reproduced with ultrahigh cooling rates similar to contact metamorphic conditions, suggesting very high exhumation rates.
In conclusion, diffusion modeling is a powerful tool that provide information on timescales necessary to equilibrate commonly used thermo(baro)meters and more importantly to identify the extent of partial reset leading to erroneous temperature estimates. Taken together, the quantitative knowledge of transport properties can be used to determine the mechanisms and rates of element and isotope transport through the crust and thus quantify their cycles in the Earth system.