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Time-Scales and Mechanisms of Metamorphic Fluid Flow from Integrated Textural and $^{18}O/^{16}O$ Micro-Analysis Studies of Metacarbonates: Evidence for Transient Flow Events

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The pathways, time-scales, mechanisms and fluxes of metamorphic fluids provide an important constraint on the distribution of deformation and metamorphic reaction in the Earth's crust. Knowledge of permeability distribution and evolution in metamorphic terrains is essential for constructing more accurate models of metamorphic fluid flow. Time-scales of flow enable the calculation of rock permeabilities at high pressures and temperatures, but are essentially unknown.

Time-integrated fluid fluxes have been evaluated from cm-m scale isotopic profiles in response to flow in metacarbonates. However, important unsubstantiated assumptions have been made about scales of equilibrium and fluid transport mechanisms. Modelling of bulk $\delta^{18}O$ data may give misleading information about fluid flow events (e.g. Lewis et al. 1998). Bulk data average micro-scale isotopic heterogeneities, which record infiltration mechanisms and distinguish flow events. Fluxes derived from modelling may therefore be unreliable. Pathways and mechanisms of fluid flow, and their relation to deformation are poorly understood.

Micro-scale analysis integrated with textural imaging enables the determination of infiltration mechanisms and the identification of separate episodes of fluid infiltration, leading to the testing and refinement of assumptions inherent in existing models of metamorphic fluid flow. Ion microprobe techniques for the stable isotope analysis of silicate and carbonate minerals provide a spatial resolution of ~25µm and a precision of <±1‰ (Valley et al. 1998). We have integrated ion microprobe $^{18}O/^{16}O$ microanalysis with textural information (optical and cathodoluminescence imaging) from metacarbonates to identify fluid pathways and mechanisms, quantify isotopic modification, and constrain durations of metamorphic fluid flow.

Grain-edge ~10^2µm-scale $\delta^{18}O$-distance profiles in calcite grains in amphibolite facies marbles from the Hida metamorphic belt, Japan (Graham et al. 1998) and Naxos, Greece (Lewis et al. 1998), modelled using experimental data for volume diffusion of oxygen in calcite, give consistent time-scales of ~10^2 to 10^4 years for grain boundary fluid flow. Subsequent preservation of profiles requires fluid loss. Infiltrating fluids were isotopically heterogeneous. In amphibolite-facies Dalradian marbles from NE Scotland $^{18}O/^{16}O$ disequilibrium between calcite and quartz in domains adjacent to micro-cracks constrain infiltration time-scales to ~10^3-10^4 yrs. Ductile deformation and dynamic recrystallisation in blueschist facies marbles from Syros (Greece) accompanied fluid infiltration which homogenised isotopic composition, destroying evidence of fluid pathways. Later greenschist facies infiltration exploited fractures, cataclastic zones and related veins, leading to isotopic heterogeneities of >10‰; isotopically unequilibrated quartz in cataclastic calcite is consistent with limiting flow durations of <10^4 yrs.

Our results indicate that rock permeability during metamorphism of carbonates is dynamically created and maintained. Fluid flow is associated with deformation (micro-cracking and dynamic recrystallisation) and reaction, and is channelled and spatially heterogeneous at all scales of observation. Fluid pathways are controlled by lithological contrast, structure and deformation. The last fluid flow event that occurred in an area is the best preserved, but earlier events may be distinguished but not be well constrained due to homogenisation of isotopic composition by dynamic recrystallisation.

Time-scales of fluid flow (10^2 to 10^4 years) are much shorter than accepted time-scales of regional metamorphism (~10^7 years). These short time-scales are comparable to time-scales of compaction-driven fluid release from rocks undergoing devolatilisation reaction (e.g. Graham et al. 1997), to estimated reaction rates (Walther and Wood 1984) and to rates of hydrofracturing (Nishiyama 1989). Rock permeability is transient. Processes that enhance permeability, such as deformation and reaction, act in competition with compaction; high fluid pressures are crucial in promoting dynamic permeability enhancement. The processes of reaction, compaction, tectonically-driven deformation and fluid flow are intimately linked.

Integration of experimental studies of the quantitative relationship between deformation and rock porosity and permeability with grain-scale analytical and textural data will enable more accurate estimates to be made of the variation of rock permeability and porosity during fluid flow. The development of quantitative models linking measured fluid fluxes to time-dependent permeability enhancement mechanisms is the next step towards more sophisticated models of metamorphic fluid flow. Numerical models may provide the way forward, allowing greater coupling of thermal, mechanical, chemical and fluid flow processes.

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