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Timescales and petrophysical changes associated with amphibolitization of mafic crust

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We explore timescales and petrophysical responses to fluid–rock interaction processes associated with far-field differential stress that promoted mode I fracture opening during the development of shear zones. Our study focuses on a ~100 m-scale E–W-striking shear-zone system (Kråkeneset gabbro, western Norway). Shear-zone formation induced brittle deformation of the gabbro, producing alternating N–S-trending mode I fractures with meter-scale spacing.

Under amphibolite-facies conditions (~650 °C, 0.58 GPa) aqueous fluids exploited the newly opened mode I fractures, resulting in the formation of decimeter-wide amphibolitized alteration zones, transforming an originally dry gabbro. Microstructural observations reveal that amphibolitization reactions preferentially occurred along mafic–felsic grain boundaries. These reactions proceeded via dissolution–precipitation mechanisms, generating transient porosity and thereby enhancing permeability and fluid transport.

To reveal chronometric and petrophysical constraints on the amphibolitization process, we applied reactive-transport modeling combined with lithium concentration and isotope data. The modeling results show that fluid and element transport was dominated by advection, whereas diffusion controlled local isotopic equilibration. From a tectonic perspective, the mode I fracture set most likely formed during a single deformation event. Such a brittle response of the gabbro to shear-induced stress buildup at elevated temperatures implies a rapid and sudden mode I fracture development.

Subsequent fluid infiltration was controlled by an externally imposed fluid-pressure gradient, which exerted first-order control on amphibolitization timescales. Modeling results suggest that the transient fluid overpressure at the wall rock interface generated short-lived porosity increases, accelerating hydration reactions. Outcrop observations show reaction zone widths along the mode I fractures clustering around ~30 ±15 centimeters. The wall rock adjacent to the fractures likely exhibited spatial variations in permeability within one order of magnitude prior to fluid infiltration. These pre-existing heterogeneities resulted in the development of reaction zones with variable widths during a single fluid infiltration event.

Modeled reaction-front propagation rates of decimeters to meters per year indicate brief, episodic brittle events that link rapid stress accumulation, fluid-pressure relaxation, transient porosity-permeability relations, and metamorphic transformation in the lower crust. Together, these results provide a quantitative framework for understanding fluid-driven metamorphism and transient permeability in deep crustal environments.