Goldschmidt 2026 Abstract
https://doi.org/10.46427/gold2026.34228

Constraining timescales of fluid-driven metamorphic rock transformation at a subduction interface using THMC modeling combined with Mg isotope diffusion chronometry

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The plate interface at subduction zones represents one of Earth's most dynamic environments in terms of deformation, metamorphism, and chemical exchange. The efficiency of these processes is strongly controlled by the presence of fluids. Accordingly, quantifying fluid–rock interaction rates is essential for understanding the pressure–temperature–deformation (P–T–d) evolution of rocks at plate interfaces.

We investigate a metasomatic reaction zone developed along the tectonic contact between serpentinite and metagabbro in the Voltri Massif (Ligurian Alps, Italy) under high-pressure conditions. Hydrated mantle-derived rocks were juxtaposed with the mafic oceanic crust at lower temperatures prior to the metasomatism. Subsequent temperature increase caused dehydration of both lithologies, liberating aqueous fluids with distinct chemistries. This setting enabled Mg-rich fluids derived from serpentinite to infiltrate the adjacent mafic crust, triggering extensive metasomatic transformation.

This study aims to constrain the timescale of the rock transformation and to explore the evolution of porosity and permeability within the modified system. Our approach integrates a fully coupled Thermo–Hydro–Mechanical–Chemical (THMC) reactive transport model with thermodynamic phase equilibria calculations and diffusion chronometry. Phase equilibria calculations, validated by observed mineral assemblages, modal abundances and mineral chemistry, are used to constrain pressure–temperature reaction zone formation conditions to 1.6 ±0.1 GPa and 600 ±20 °C. Across the reaction zone, bulk MgO concentration decreases continuously from serpentinite (~40 wt.%) to metagabbro (~5 wt.%). This gradient is accompanied by a systematic Mg isotope fractionation, with δ^{26}Mg values decreasing from +0.09‰ in serpentinite to −1.1‰ within the reaction zone and increasing to −0.1‰ towards the least affected metagabbro. Such an Mg isotope profile indicates kinetic fractionation during Mg diffusion and provides the basis for Mg isotope diffusion chronometry.

Our THMC model results reproduce the observed major-element and isotopic profiles and suggest transient porosity generation localized at the reaction front. Calculated Peclet numbers (~0.01–0.1) indicate diffusion-dominated mass transport, with a minor advective component. The chronometric modeling results constrain the duration of metasomatic transformation to 10^3–10^4 years, highlighting the rapid nature of fluid-mediated processes at the subduction interface. This integrated approach bridges small-scale metamorphic processes and larger-scale subduction dynamics.