Goldschmidt 2026 Abstract
https://doi.org/10.46427/gold2026.35209

Does A Density-Controlled Interfacial Nano-Reactor Govern Element Mobility in Supercritical Hydrothermal Systems?

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Element transport in hydrothermal systems is normally interpreted through fluid-rock interaction and bulk fluid composition. However, experimental results at 400 – 500 °C suggest that element redistribution may instead be governed by processes confined to a nanometer-scale interfacial environment. Experiments have been conducted reacting greywacke with distilled water at supercritical conditions. A sharp transition in alteration behaviour was observed over a 100°C interval.

At 400°C, extensive surface restructuring occurs. Rock-forming components are redistributed with secondary minerals growing up to 10 µm in size, despite negligible cation concentrations in the bulk fluid. This decoupling from bulk solution chemistry suggests sustained surface-confined transport. In contrast, at 500 °C, this cation mobility collapses, only SiO_2 is mobile, and reacted surfaces are coated by cristobalite with very rare calcite. Bulk fluid solutes in both experiments are dominated by SiO_2.

We propose that these contrasting behaviors reflect the operation—and collapse—of a density-controlled interfacial "nano-reactor." Increasing temperature from 400 to 500°C reduces water density by ~60% at constant pressure, with a corresponding decrease in dielectric constant. Because surface-induced density and solvation capacity scale with fluid density, the increase in solution temperature likely thins and destabilizes a condensed interfacial water layer. At 400°C, such a nanometer-scale layer may sustain hydrolyzed metal complexes and enable lateral diffusion and reaction, producing µm-scale mineral growth over duration of the experiments. At 500°C, collapse of this interfacial environment suppresses cation mobility, shifting the system into a vapor-like, silica-dominated alteration regime analogous to high-temperature fumarolic systems.

These results suggest that modest temperature increases at supercritical pressures can induce fundamental changes in hydrothermal behavior by switching interfacial transport "on" or "off." If operative, this density-controlled interfacial mechanism implies that element mobility, mineral alteration pathways, and material performance in supercritical geothermal reservoirs may be governed as much by nanoscale fluid structure as by bulk fluid chemistry. Such nanoscale control has important implications for predicting scaling, corrosion, permeability evolution, and long-term reservoir performance during supercritical geothermal exploitation.