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Controls of Fracture Architecture on Spatial Variability of Fluid-Rock Interactions in Siliciclastic Sandstones

ADEDAPO NOAH AWOLAYO[1], JIACHEN GAO[1,2], QIN ZHANG[3], JIANWEI TIAN[1,4] AND BENBEN MA[2]

[1]McMaster University
[2]China University of Geosciences
[3]Delft University of Technology
[4]Hebei University of Technology

Understanding how structural heterogeneities regulate coupled flow and reaction processes is essential for predicting the evolution of subsurface systems used for energy storage and environmental applications. Tight siliciclastic sandstones are increasingly targeted for hydrogen storage, CO_2 sequestration, and geothermal operations, yet their inherently low matrix permeability constrains injectivity and reactive exchange. Natural microfractures embedded within these formations can reorganize transport pathways and fundamentally alter water-rock interaction dynamics. However, mechanistic links between fracture architecture and reactive transport behaviour remain poorly constrained. Here we integrate petrographic characterization with multicomponent reactive transport modelling to quantify how intragranular (IMF) and transgranular (TMF) microfractures govern spatial variability in fluid-rock interactions. Systematic variations in fracture density, connectivity, and aperture reveal the emergence of dual transport-reaction regimes. In addition, these microfractures act as dominant flow conduits that are reaction-limited, whereas the surrounding matrix remains transport-limited. Increasing TMF density and connectivity enhances reactive surface accessibility and sustains fluid undersaturation, promoting early-stage dissolution. Larger fracture apertures intensify reactivity but accelerate mineral depletion and local geochemical equilibration.

In addition, the introduction of IMF networks produces coupled IMF-TMF systems that redistribute flow from a small number of highly conductive fracture channels into previously isolated grain-scale regions. This redistribution extends reactive fronts, delays passivation by secondary mineral precipitation, and stabilizes permeability evolution over time. System-scale behaviour therefore emerges from the dynamic coupling between fracture-dominated advection and matrix-controlled diffusion. These results establish a quantitative structure-flow-reaction framework linking microfracture architecture to porosity evolution and flow-path stability, contributing toward improved multi-scale reactive transport representations needed for reliable assessment of engineered subsurface reservoirs supporting the energy transition.