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Evolution of Hydraulic and Mechanical Apertures in Heterogeneous Fractures Driven by Mineral Precipitation

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Chemical reactions induced by fluids that are out of chemical equilibrium with the minerals on fracture surfaces lead to mineral dissolution and/or precipitation along fracture surfaces and alterations in the fracture aperture. Incorporating the influence of localized chemical alterations into continuum models requires effective constitutive models that relate changes in mechanical aperture to changes in hydraulic aperture and reactive surface area, which control the concentration distribution within the fracture. Local reaction rates depend on ion concentrations, reaction kinetics, and available reactive surface area. The local ion concentrations are strongly influenced by the relative rates of advective transport of ions through the fracture and local reaction rates, which are characterized by the dimensionless Damköhler number ($Da = kLW/Q$, where Da is the Damköhler number, k is the reaction rate coefficient, L and W are the fracture length and width, and Q is the flow rate). In this study we explore how Da, aperture variability, and mineral heterogeneity influence the evolution of reactive surface area, the mechanical and hydraulic aperture. Our analysis is based on 480 high-resolution mechanistic simulations using a previously developed model that simulates advective-reactive transport within variable aperture and explicitly represents the resulting three-dimensional growth of minerals on the fracture surfaces (Jones and Detwiler, 2019). We varied Da, relevant geometric parameters including fracture aperture (mean, standard deviation, and correlation length) and intial reactive surface area (magnitude and spatial distribution) over the full range of expected parameter values. Our results demonstrate a strong dependence of fracture-scale hydraulic aperture evolution on Da, particularly with the spatial distribution. At high Da, precipitation occurs more rapidly at reaction sites near the fracture inlet than those near the outlet, leading to hydraulic aperture decreasing faster than mechanical aperture. At low Da, reaction rates are more uniform across all reaction sites, and the mechanical and hydraulic apertures evolve at similar rates. Additionally, because reaction rates are uniform throughout the fracture, the evolution of aperture and reactive surface area depends on the geometry of the evolving surface, rather than the distance along the fracture. We propose a constitutive model that relates precipitated volume to reactive surface area. This model enables the development of a simplified one-dimensional continuum framework, effectively representing the influence of mineral precipitation on fracture transport properties over the broad range of parameter space considered in our simulations.

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References

Jones, T. A. and Detwiler, R. L. (2019). Mineral precipitation in fractures: Using the level-set method to quantify the role of mineral heterogeneity on transport properties. Water Resources Research, 55(5):4186–4206.

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