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Impact of Stress and Fracture Orientation on Fluid Mixing at Fracture Intersections

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Fractures and fracture networks are critical pathways for subsurface flow and reactive transport in rock. In particular, fracture intersections, where fluids with different properties mix and react, serve as biogeochemical reaction hotspots. Recent studies have highlighted the importance of intersection geometry in influencing mixing dynamics. Although geologic fractures are subjected to geological stress, the impact of stress-induced geometric changes on mixing at intersections remains unexplored. In this study, we combine laboratory experiments and 3D pore-scale numerical simulations to investigate how stress-induced changes of intersection geometry affect mixing at fracture intersections and discuss the implications for upscaled modeling of mixing at fracture intersections.

For the laboratory experiments, four 3D-printed prismatic blocks were used to create a fracture intersection between two orthogonal fractures. The behavior of the orthogonal fracture intersections was examined for two orientations relative to the applied load. An "×"intersection occurs when the direction of gravity is at a 45-degree angle with respect to the fracture planes, while a "+"intersection occurs when the direction of gravity is parallel to the vertical fracture. The samples were weakly laterally confined while subjected to a normal load that was oriented along the direction of gravity. 3D X-ray tomographic reconstructions of the geometry of the intersecting fractures were used to generate numerical meshes for flow and transport simulations. The numerical simulations were conducted by solving the steady-state, incompressible Navier-Stokes equations for the flow and the advection-diffusion equation for solute transport and mixing.

Our results reveal that both the stress magnitude and the orientation of fractures relative to the direction of maximum principal stress exert dominant control over deformation, which in turn controls fluid flow and mixing. In the "+"intersection, as the load increases, the horizontal fracture mainly closes while the vertical fracture remains unaffected. The closure of the horizontal fracture increases flow and solute mass flux toward the vertical fracture. In the "×"intersection, an increase in load induces shear dilation, causing one fracture to open while the other closes. Additionally, contact areas form near the region where the two fractures intersect due to shear dilation and expand as the load increases. This shear-induced contact areas transform the intersection from an "×"shape into two "v"-shaped fractures connected by critical links, referred to as pinch points. Shear-induced dilation opens one fracture, leading to increased flow and solute mass toward the opening fracture. However, continued loading reduces void the number and the volume of pinch points, limiting further flow increases despite the growing aperture difference. Current network-scale modeling does not account for the effects of stress on mixing at intersections, potentially leading to overpredictions of mixing. To address this, we propose a simplified mixing model that captures the key processes. This study suggests that the stress state and fracture intersection orientation are the key factors controlling mixing and transport in fracture networks.

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References

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