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Effects of Pore-Scale Three-Dimensional Flow and Fluid Inertia on Mineral Dissolution

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Mineral dissolution is a key process of subsurface systems and engineering applications, such as karst formation and engineered carbon mineralization. Fluid flows have been shown to significantly affect mineral dissolution rates by controlling concentration fields [1-2], highlighting the importance of understanding flow-dissolution dynamics. In subsurface porous and fractured media, inertial flows can readily occur and induce complex flow structures, such as recirculating flows, which complicate mineral dissolution dynamics. Moreover, recent studies demonstrated that flow topologies can fundamentally differ between 2D and 3D systems, particularly in recirculating flow patterns, substantially altering reactive transport dynamics [3-4]. Thus, nonlinear effects may have significant implications for pore-scale mineral dissolution. However, the effects of fluid inertia and 3D flow on pore-scale mineral dissolution, as well as their impact on upscaled processes, remain largely unknown.

In this study, we investigate the effects of fluid inertia and 3D flow on mineral dissolution using milli-fluidic experiments and pore-scale numerical simulations. We conduct laboratory dissolution experiments with a real-time imaging system and a rock analog material, and we perform pore-scale reactive transport simulations using a micro-continuum approach to capture spatiotemporal evolution of a mineral phase due to dissolution. Both experimental and simulation results demonstrate the importance of fluid inertia in governing dissolution patterns. For example, along the mean flow direction, we find that low inertia induces fast dissolution on the inlet side, while the high inertia case exhibits the opposite effect (Figure (a)). In addition, distinct dissolution patterns, such as bifurcated in low inertia and concave in high inertia, appear on the mineral surface in 3D (Figure (b)). We conduct a detailed flow topology analysis and find that changes in the topological properties of 3D flows under varying inertia regimes predominantly control the formation of these distinct 3D surface patterns, which cannot be captured in 2D studies. Finally, we analyze the implications of these 3D dissolution dynamics on the upscaled relationship of porosity and reactive surface area; the analysis shows similar trends between the 2D cases and a conventional relationship, while the 3D cases significantly deviate from it. Our study highlights the significance of fluid inertia and 3D flows on pore-scale mineral dissolution and their implications on Darcy-scale processes.

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