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Tracking Biomineralization in Shale Fractures with Magnetic Resonance Velocimetry (MRV) and Computed Microtomography (Micro-CT)

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Meeting ambitious carbon neutrality goals set by governments worldwide requires a multifaceted approach. One area of focus is the utilization of subsurface energy resources, particularly in shale formations located thousands of feet underground. Although this reservoir was an important contributor to the natural gas boom of the 2000s, it has increasingly been explored for other, more environmentally sustainable processes such as CO2 sequestration [1, 2], geothermal energy [3, 4], and hydrogen geo-storage [5]. However, a key concern with these applications is fractures that arise in shale, which could potentially lead to buoyancy-driven migration of greenhouse gases and valuable energy resources [6]. One solution to enhance shale integrity is biologically engineered mineral precipitation, also known as microbially-induced calcium carbonate precipitation (MICP) [7]. An early study showed that elevated pressures (6.12 MPa) do not hinder biomineralization in fractured shale, with up to four orders of magnitude permeability reduction achieved [8]. Follow-up research demonstrated that MICP treatment was similarly successful at sealing fractured shale cores at elevated temperatures ($60^{\circ}C$) [9, 10]. Although these studies showed that subsurface conditions are favorable environments for precipitation, they called for further analysis to better understand fluid-rock interactions integral for sealing.

On the reservoir scale, a ʻcubic lawʼmodel derived from the Reynolds equation and lubrication theory is often used to approximate flow fields based on an average fracture width [11, 12]. More accurate ʻlocal cubic lawʼ(LCL) models can calculate local flows based on the local aperture, which can be measured by highly detailed computed microtomography (micro-CT) scans of the fracture [13]. Alternatively, magnetic resonance velocimetry (MRV) can be used to experimentally measure fluid quantities in opaque systems non-invasively in 3D [12, 14, 15]. By combining spatial encoding (k-space) with molecular displacement measurements (q-space), velocity maps can be measured for various flow types, including flow through porous media. Spatial information can also be sacrificed to obtain a probability distribution of molecular displacements called a propagator, which offers high temporal resolution with respect to changes in flow and pore structure [16].

This study represents the first application of MRV to visualize and investigate fluid flow in shale fractures. Velocity maps and propagators characterize flow within fractured shale cores (5.08 cm length, 2.54 cm diameter) and track changes in pore structure and flow fields due to MICP-treatment (Fig.1). Complementary micro-CT imaging reveals changes in fracture aperture maps and fluid flow from LCL simulations. The results show that mineral formation due to MICP changes preferential flowpaths and confirm that MRV is an effective tool for tracking sealing progress in rock fractures, providing invaluable information for optimizing MICP injection strategies and fluid flow numerical simulations for advancing subsurface energy applications.

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