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Microfluidic investigation of water-scCO2 phase distributions in vesicular basalt pore system proxies

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In this study, we conducted a series of microfluidic experiments using Stereolithography (SLA) 3D-printed chips designed to replicate the pore geometry of vesicular basalts and investigate a scaled version of in-situ supercritical CO_2 (sc-CO_2)/water/basalt multiphase flow dynamics under room conditions and a large parameter space. Multiphase flow phase distributions will impact scCO2 dissolution, reactant mixing paths, carbonate growth patterns, and relative permeability during subsurface supercritical CO2 injection for carbon storage and mineralization. Multiple field-scale pilot projects, such as those conducted at Wallula and CarbFix, underscore the viability of sequestering sc-CO_2 in basaltic formations, specifically in the highly permeable flow-top vesicular zones. These zones are characterized by millimeter-sized vesicles connected through microfractures across basalt matrix and nanopores in clay, forming a dual-porosity system with a large aspect ratio that differs substantially from conventional sedimentary reservoirs. The transport of sc-CO_2 under in-situ conditions in basalt dual-porosity networks remains poorly understood, hindering accurate predictions of CO_2 migration and mineralization inside basaltic formations. To approximate these pore morphologies, each microfluidic chip features an interconnected channel network that mirrors the high-aspect-ratio pore structure and dual-porosity characteristics of vesicular flow-top basalts. To approximate in-situ fluid properties, we screen through combinations of fluorinated hydrocarbons as the nonwetting phase and glucose–water solutions as the wetting phase, effectively preserving the high viscosity ratio and wettability conditions of in-situ sc-CO_2/water/basalt systems under room conditions. Wetting and non-wetting fluids are co-injected by a syringe pump at various controlled rates and volume ratios to represent a range of reservoir conditions (i.e., flow rate and saturation state) from near-wellbore to far-field region. Bubbles of non-wetting fluid are generated through a T-junction at the inlet with a uniform size distribution controlled by channel width and flow rate. The dynamic evolution of bubbles within the interconnected channel system, including snap-off and coalescence events, are traced in the acquired video with AI-assisted image analysis. A U-shaped manometer is integrated at the inlet and outlet ports to measure the pressure differential across the chip, enabling the calculation of relative permeability of each phase under different flow regimes. These combined flow visualization and pressure measurements yielded critical insights into: (1) the feedback loop among CO_2 bubble size distribution, occurrence of snap-off/coalescence events, and relative permeability, (2) steady-state partial water saturation within both mobile and immobile fluids, and (3) the preferential flow pathways in dual-porosity pore systems analogous to vesicular basalts.

We posit that the presented microfluidic diagnostics will enable scalable insights into in-situ sc-CO_2 migration and phase distributions and, ultimately, mineralization behaviors within basaltic formations. Preliminary results suggest that flow rate and initial bubble size strongly influence local partial saturation, relative permeability, and bubble behavior. Looking forward, our work will extend toward incorporation of nanoporous materials and reactive minerals into the current chip design to better represent geochemical processes inside vesicular basalts. This expanded approach aims to elucidate the interplay between fluid transport, geochemical reactions, and dual-porosity nature, ultimately optimizing injection schemes for efficient and secure in-situ carbon mineralization in basaltic formations.

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References

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