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Pore-scale multiphase reactive transport and CO2 mineralization capacity in vesicular basalts

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The geological storage of CO2 has emerged as a critical pathway for decarbonization, where in situ carbon mineralization in mafic/ultramafic rocks such as basalts is considered the most stable form of CO2 storage. in-situ CO2 mineralization pilot projects in basaltic formations include the Wallula project in Columbia River basalt and the Carbfix project in Icelandic basalt. Multiphase flow governs the invasion and distribution of native brine, carbonated water, and injected supercritical CO2 and will determine the accessibility and carbonation capacity of reactive mineral pore surfaces during geochemical processes. As such, what is the mix of injectate or injection scheme that optimizes tons of anthropogenic CO2 injected (storage) and mineralization capacity (security) for different formations?
We leverage pore-scale, multiphase computational fluid dynamics (CFD) models, enhanced by experimentally- and theoretically-informed reactive transport relationships and mineral-fluid wettability values, to assess the complex interplay between mineral hydrophilicity, capillary trapping, thin films, dissolution, precipitant nucleation, and mineralization. We simulate various injection schemes, including supercritical (dry) CO2 invading in-situ brine and water-alternating-gas (WAG) injection, within several representative vesicular basalt samples (including one fresh basalt sample, one from the Carbfix site, and two from different flow-top zones in the Wallula site). The pore-scale models are informed by petrographic data of pore morphology (e.g., thin section, SEM, micro-CT), physical-chemical mineralization behavior (coupled with PHREEQC), and routine core analysis data. The models are tuned with different boundary conditions and initial conditions to represent the basalt units in different locations in the reservoir under the selected injection schemes. For each sample, we quantify crucial dynamic relationships for geologic storage and mineralization, including porosity-permeability, accessible reactive mineral surface area, brine-CO2 capillary pressure-saturation (Pc-Sw), and relative permeability (Kr-Sw) relationships. These relationships are explored as a function of native basalt groundwater composition, mineral-specific surface area, and the sequence of pore-scale alteration processes. The aforementioned dynamic pore-scale relationships are integrated with fluid characterization and core-scale measurements, including hydraulic tests, helium pyconometry, and NMR measurements. Results indicate a strong correlation between the location of precipitated nodules and the menisci of CO2 bubbles under steady state, depicting a vital role of multiphase flow in understanding geochemical processes.
Ongoing efforts involve extrapolating pore-scale functional relationships to gridblock-scale reactive transport reservoir models (e.g., STOMP and MRST) to refine predictions of invasion depth, carbon storage and mineralization capacity, with the consideration of evolving accessible reactive surface area on a larger scale.

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