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Nanoporosity controls on the carbon storage and mineralization potential of basalts: insights from hydrothermal alteration at Newberry Volcano

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This study quantifies the pore structures and reactive flow capacity of basalt rocks, specifically a range of flow top (vesicular) and seal basalt samples from Newberry Volcano drill core (Oregon, USA). Dissolution and precipitation reactions in basalts and other mafic and ultramafic rocks (silicates rich in Mg, Ca, and Fe) are the foundation for carbon mineralization, in situ mining, and geologic hydrogen technologies due to high contents of reactive minerals (e.g., pyroxene and olivine) or critical minerals. However, despite their high reactivity, these rocks exhibit large variations in porosity and permeability. In fact, many of these rocks are nanoporous (<1 μ m) or poorly connected, thereby challenging fluid access to critical and reactive mineral surfaces. The bulk volumes of qualifying basaltic and mafic/ultramafic rocks are vast, with the US's Pacific Northwest alone estimated to have 10^5 Gt CO₂ basalt storage/mineralization capacity, assuming pore space and reactive minerals are accessible to fluid flow. Towards addressing accessible pore space and reactive minerals surfaces, this work examines the (a) pore size distribution and connectivity and (b) accessible mineral surface area within Newberry volcano basalt samples.

The Newberry Volcano basalts provide a natural laboratory for understanding multiphase and reactive flow potential of basalt pore structures. We collected 20 basaltic sandstone/volcaniclastic rocks and basalt/basaltic andesite rocks from USGS Newberry volcano drill core. The studied samples have been subjected to varied amounts of gases (CO₂, H₂S) and aqueous fluids in situ. The samples display varied degrees of hydrothermal alteration, where rock properties (porosity, permeability, lithology), temperature, and fluid composition dictate the extent of alteration. We characterize the macropores (vesicles) and nanopores (clays and matrix) of samples with N₂ adsorption-desorption isotherms (BET surface area), TD-NMR T₂, pycnometry, thin section and SEM/EDS, and microCT. The amount of Fe₂O₃, MgO, and CaO ranges from 18% (volcanic siltstone)-25% (flow-top basalt), confirming the reactivity of these Newberry volcano rocks. Direct numerical pore-scale simulations are used to study fluid flow capacity in image- and process-based domains for characteristic sample pore-scale features. We find distinct differences in pore structures among lithologies: for example, the volcaniclastic siltstones are dominated by a bimodal distribution, fresh/seal samples are dominated by a unimodal distribution, and multimodal distribution is significant in all hydrothermal altered basalts. Combining these distributions with imaging and modeling supports that nanoporosity is a driver of reactive flow capacity in basalts: Primarily nanoporous samples with extremely low permeability remain relatively "fresh" (unaltered) over geologic time. In originally more porous samples, aqueous fluids have altered primary minerals (plagioclase) into clays, quartz polymorphs, and carbonates which fill the pore systems, resulting in a secondary nanoporosity system. All studied hydrothermal altered basalts have similar pore size distribution and mainly contain slit-shaped pores (per BET analysis); the signal is likely dominated by clays. Overall, the natural CO₂-fluid-rock system of the Newberry Volcano can be leveraged to understand anthropogenic CO₂ movement in basalts. The alteration-nanoporosity-flow capacity feedback loop summarized in this work has implications for basalt storage capacity and seal performance for the aforementioned energy transition applications, especially CO₂ storage and mineralization.

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