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Impacts of Accessible Surface Area on CO2 Mineralization in Basalt Formations

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As global warming intensifies, CO_2 sequestration has been recognized as one of the most feasible strategies for reducing CO_2 emissions. Within CO_2 sequestration approaches, the CO_2 mineralization process, a promising CO_2 sequestration method, consists of four main steps: (1) injection of CO_2-saturated water into basalt formations, (2) dissolution of mafic minerals within the porous media, (3) release of divalent cations (Ca^{2+}, Mg^{2+}, Fe^{2+}) into aqueous phases, and (4) precipitation of carbonate minerals, thereby immobilizing CO_2 as stable solid phases. To evaluate the CO_2 mineralization capacity in basalt formations in relation to fluid accessibility, numerical simulations were conducted for the CarbFix project site and the Jeju basalt formation based on comprehensive analyses. The physicochemical properties of two basalt samples were characterized through detailed petrophysical and geochemical analyses. Porosities and permeabilities were quantified using micro-CT imaging and MICP porosimetry. Primary mineral compositions were identified as albite, anorthite, diopside, hypersthene, alkali feldspar, forsterite, fayalite and ilmenite through XRD, EPMA and whole-rock analysis. The kinetic parameters of mineral reactions are crucial factors during the CO_2 mineralization process. Among the kinetic parameters, the mineral reactive surface area, a site-specific property, has a predominant impact on the reaction rate of mineral dissolution/precipitation. In early studies, reactive surface area was employed as specific surface area (SSA), which represents geometric surface area of mineral particles per unit mass. Recent geochemical studies suggest adopting the accessible surface area (ASA), which quantifies the accessibility of minerals to reactive fluids within porous media, to better account for heterogeneous reactions. To investigate the impact of fluid accessibility on CO_2 mineralization through numerical simulation, SSA and ASA were quantified through SEM image analyses and utilized as input parameters in numerical simulations. Numerical simulations were performed over a 100-year period, with CO_2-saturated water (1 mol/kg) injected for the first 5 years at a rate of 100 kg/s. The simulations evaluated the long-term effects of SSA and ASA on CO_2 mineralization in basalt formations. Over 90% of the injected CO_2 was sequestered as immobile mineral phases including dolomite, magnesite, and siderite within the first 10 years. The dissolution trends varied with distance from the injection well, driven by changes in pH and applied reactive surface areas. Spatial variations in cation release (Ca^{2+}, Mg^{2+}, Fe^{2+}) significantly influenced the precipitation of carbonate minerals, leading to up to three orders of magnitude difference in precipitated amounts between simulations employing SSA and ASA. This study demonstrates that fluid accessibility in basalt formations plays a critical role in CO_2 mineralization by influencing mineral dissolution and precipitation dynamics. Moreover, the consideration of reactive surface areas, including SSA and ASA, is crucial for accurately evaluating CO_2 mineralization capacity. These results provide meaningful insights into the utilization of CO_2 mineralization in basalt formations as a reliable and efficient solution for carbon storage.

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