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Reactive transport modeling of a tracer test in a fractured bedrock aquifer for investigating uranium mobility under shifting redox conditions

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Long-term safety assessment of high-level nuclear waste (HLW) disposal has become increasingly important due to the growing global energy demand. However, quantitative field-scale evaluations of uranium migration remain limited, particularly regarding the influence of redox conditions, which critically affect uranium mobility. In this study, we quantitatively assess the effect of redox conditions on uranium migration in a fractured aquifer using reactive transport modeling of a field tracer test. The study site, located in the Okcheon metamorphic belt of South Korea, is characterized by uranium-bearing black slate, which contributes to elevated uranium concentrations in the rock, while uranium levels in the reduced groundwater remain low. To investigate the impact of redox conditions on uranium mobilization, a tracer test was conducted by injecting aerated (oxidized) groundwater into the fractured aquifer. This field experiment was simulated using reactive transport models (RTM) by coupling the flow and transport model COMSOL Multiphysics with the geochemical model PhreeqcRM using the SNIA scheme. Based on the observed ion concentrations, RTM calibrated chemical reaction parameters by computing the kinetic oxidative dissolution of UO_2, surface complexation, mineral dissolution/precipitation and redox reactions in PhreeqcRM. The tracer test results show that uranium concentrations increased by 11.1% to 75.2% from a background groundwater concentration of 0.59 μg/L. Additionally, RTM indicates that this increase is primarily due to the oxidative dissolution of UO_2 under oxidizing conditions, and it implies that oxidizing condition is a major factor to induce uranium mobilization in the aquifer. This study suggests that redox conditions should be considered to assess safety disposal of HLW in a deep geological repository.

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