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Scenario-Based Modeling of 10^5-Year Hydrogeochemical Evolution in Crystalline Bedrock: Insights from the Korean Peninsula

MIHYE KONG AND YUL ROH

Chonnam National University

Predicting the long-term geological and hydrogeochemical evolution of crystalline bedrock is essential for assessing the safety of deep geological disposal of high-level radioactive waste (HLW). This study presents a scenario-based conceptual modeling framework for projecting long-term environmental changes on the Korean Peninsula by integrating field observations, literature data, and reactive geochemical simulations.

Crystalline rocks, including granite and gneiss, are considered potential host lithologies in South Korea under humid temperate climatic conditions. Field investigations across multiple granitic terrains were combined with mineralogical analyses, bulk geochemistry, groundwater chemistry, and chemical weathering indices (e.g., CIA) to constrain progressive rock weathering and soil formation over timescales up to 10^5 years.

The results indicate progressive dissolution of primary silicate minerals (feldspars and biotite) and formation of secondary phases such as kaolinite, gibbsite, and Fe-oxyhydroxides, accompanied by gradual depletion of alkali cations and evolution toward weakly acidic groundwater conditions. Reactive geochemical simulations using PHREEQC were conducted to model groundwater evolution accross time intervals of 0–10^3, 10^3–10^4, and 10^4–1.1×10^5 years under open-system conditions with atmospheric CO_2. The simulations reproduce long-term geochemical trends, including increasing dissolved silica concentrations, moderate pH buffering, and a transitions in groundwater composition from Ca–HCO_3 to alkali–silica-dominated types. Mineral weathering kinetics, ion exchange, and secondary mineral precipitation govern these evolutionary pathways.

This modeling framework contributes to regional-scale scenario development for repository siting and long-term performance assessment. The results suggest that crystalline host rocks in humid environments can sustain chemically buffered conditions over disposal-relevant timescales, although lithology-dependent variations may influence radionuclide mobility and natural barrier performance. This case study provides transferable insights for safety assessment of HLW repositories in crystalline rocks worldwide and underscores the importance of integrated hydrogeochemical modeling for long-term evaluation.

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