Quantitative interpretation of trapping mechanisms of CO₂ at Nagaoka pilot project
– A history matching study for 10-year post-injection –

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Long term stability of CO₂ stored in reservoir is of intrinsic importance for ensuring the viability of geologic sequestration of carbon dioxide. Demonstrating the permanence of storage is an important task of pilot projects. In the Nagaoka project, Japan’s first pilot-test of geological CO₂ sequestration that injected about 10,400 tonnes of CO₂ from 2003 to 2005, a stable containment of CO₂ in a reservoir has been successfully demonstrated by kept monitoring the CO₂ behavior even after the end of injection during about 10 years. Systematic and continuous data acquisition of time-lapse well loggings (e.g., resistivity, neutron, and sonic velocity) successfully illustrated the detailed nature of CO₂ migration at intra-reservoir resolution, including uneven CO₂ arrival and subsequent saturation changes to the well-depths and the prevention of vertical movement of buoyant CO₂ by potential seal layers. The time evolutions of CO₂ saturation were quantitatively evaluated under sub-meter resolutions by neutron logs. Resistivity logs even enable us to infer the dispersed area of dissolved CO₂ out of the reservoir. Fluid samplings at multiple depths also provided an insight into geochemical processes among CO₂, water. However, in order to better understand the trapping mechanisms from these detailed observations, the numerical modeling with sub-meter spatial resolution is necessary, which has not been performed yet in the project.

In this study, a three-dimensional reservoir model with sub-meter spatial resolution has been developed that comprehensively involves coupled process of two-phase fluid flow and geochemical transport. The model was history-matched against a set of monitoring data acquired during the post-injection period including pressure, well loggings, and fluid samplings. The calibration of a large model is computationally demanding, hence we employed a parallel version of coupled fluid flow and geochemistry TOUGHREACT V2.0/ECO2N with MPI parallelism, which has also been newly developed in-house. The new code also features hysteretic effect in relative permeability and capillarity which was not implemented in the original TOUGHREACT V2.0.

The model involves three components (H₂O, CO₂, and NaCl) and two-phase (CO₂ and water) flow, which is further coupled with chemically reactive transport with 10 primary aqueous species and 9 minerals including some carbonate, almino-silicate, and clay minerals. A heterogeneous distribution of permeability and porosity in three-dimension was realized on the basis of geological interpretation by the concept of sequential stratigraphy and sequential Gaussian simulation on the Petrel software. The Petrel model was converted to integral finite difference grids for TOUGHREACT simulations by utilizing TOUGH2’lBox tools developed by BRGM. Local grid refinement (LGR) was applied in the vicinity of the CO₂ injection area. A fine grid spacing of 0.5m in vertical was employed in the vertical direction to directly represent heterogeneous distribution of porosity and permeability along depths arising from alternating thin layers of mud, sand, and conglomerate.

The detailed 3D history matching study successfully reproduced the behavior of CO₂ observed at sub-meter scale over time, although it needed to assume a strong anisotropy of permeability to explain the arrival time of CO₂ at some observation wells. From the result, the following insights into the trapping mechanisms of CO₂ at the project can be drawn at present.

- During the injection, free CO₂ migrated preferentially through higher permeable layers. The uneven arrival times of CO₂ to the well-depths are well explained by, and consistent with the non-uniform permeability distribution measured at wells. Subsequent temporal changes in CO₂ saturations are also well simulated by the model.

- Pressure-driven-flow during the injection squeezed the formation water out of the reservoir, and consequently resulted in hydrodynamic dispersion of dissolved CO₂ into over- and under-lying lower permeable layers. This behavior is highly consistent with the resistivity changes observed by well loggings. The spread of dissolved CO₂ stays almost stable after the end of the injection.
• In the post-injection period, history-matching of slow or negligible migration of buoyant free CO$_2$ to the vertical direction suggests that even a thin (10cm scale), intra-reservoir muddy-layer behaves like an impermeable flow barrier to trap CO$_2$, implying a combined strong effect of lower vertical permeability and high capillarity to prevent the invasion of CO$_2$.

• The hydrodynamic dispersion of CO$_2$ increased bicarbonate concentration in formation water above and beneath the free CO$_2$ zone, and promoted dissolution of rock minerals including dissolution of calcite and almino-silicates resulting in increase of calcium and silica concentrations. The long-term coupled geochemical simulation suggests that these are precursor of mineral trapping by the precipitation of carbonates such as calcite in the future in this site.