How to include immobilization potential and plume retardation due to physical and chemical trapping in risk evaluations for CO₂ storage in open, sloping aquifers - results from the CO₂-Upslope project

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Abstract

The CO₂-Upslope project [1] is challenging some common concepts in estimating storage volumes for CO₂ in saline aquifers, by including plume retardation due to physical and chemical trapping as retardation factors (R_{phys} and R_{chem}) in decoupled models. In this way, the total immobilization potential may be estimated for high resolution, geologically heterogeneous reservoir models and form part of reservoir risk evaluations, without exceeding reasonable numerical capacity. Further, CO₂ storage schemes should be optimized with respect to immobilization potential (i.e. dissolved, residual and mineralized CO₂) in a way that limits plume migration and decreases pressure buildup.

In order to develop the methods and numerical tools presented herein, a prospective reservoir candidate on the Norwegian Continental Shelf representing an open, sloping aquifer was chosen for a detailed case study. The Gassum Formation (reservoir) is a fairly porous and permeable sandstone of Late Triassic to Early Jurassic age, overlain by the silty and clay-rich Fjerritslev Formation (seal). The wedge-shaped aquifer is thinning and sloping towards the north, sub-cropping towards near-shore Quaternary sediments and the sea floor. It is of utmost importance to evaluate migration distances to prevent leakage, and it provides an interesting challenge to optimize storage in a way that ensures for all injected CO₂ to become immobilized before reaching the outflow boundary.

Volumetric storage potential for CO₂ is traditionally estimated based on injection into a structural trap or a semi-closed aquifer of a given volume, thus pressure dissipation capacity and the in situ pressure conditions provide the main limiting factors [2]. With time, however, CO₂ will dissolve in water and to some extent precipitate as solid phase minerals [3, 4]. There are significant knowledge gaps in understanding how these intra reservoir processes may lower injection-induced over-pressure and retard a migrating CO₂ plume over long time scales. Failing to integrate these effects in reservoir characterization schemes may severely underestimate storage capacity and injectivity and skew risk evaluations, shutting off suitable reservoir candidates.
The developed workflow involves stepwise consideration of trapping and retardation in decoupled models, in defining \( R_{phys} \) and \( R_{chem} \). Firstly, a detailed geological mapping study was performed, re-interpreting seismic data and sequence stratigraphy. Evaluations of the number and extent of intra-reservoir flooding surfaces (shale layers) and erosive unconformities, as well as the sedimentary facies distribution and diagenetic burial trends were included in the reservoir characterization and forming the basis for property modelling. A small, local grid (1x1 km) with high vertical resolution throughout the reservoir zone, including meter-scale geological heterogeneities was constructed for injectivity-modelling. In-house software MRST [5, 6] and PFLOTRAN [7] is applied to estimate short term pressure dissipation capacity and the dissolved fraction (100 years post injection), testing various well locations. Salting out effects are included in injection models [8]. To optimize trapping efficiency and minimize pressure buildup an inclined well is applied.

The next step is to simulate long-term migration in a regional property model, including only the top part of the reservoir. The total volume of free phase CO\(_2\) having reached the reservoir top seal after injection + 100 years is the input, assuming vertical equilibrium is valid on long time scales (i.e. > 1000 years). Large structural traps along regional faults are included discretely in the grid, while trapping in smaller faults is estimated in \( R_{phys} \) drawn from vertical equilibrium in topography models by use of MRST. To assess the chemical reaction impact on plume migration (\( R_{chem} \)), we use a modification of the parallel reactive flow and transport code PFLOTRAN, with SAFT-type equations of state and reactivity potential input estimated in PHREEQC-C [9]. The final stage of running the regional model with retardation factors is performed in ECLIPSE 300 [10].

The overall aim was to improve model resolution with respect to geological heterogeneities and geochemical processes, and at the same time reduce numerical cost (time) compared to reactive modelling approaches. The resulting models estimate the storage capacity with the total amount of CO\(_2\) and the maximum reach of a plume migrating upslope in the Gassum aquifer sufficiently retarded, by structural and geochemical trapping mechanisms, to never reach the semi-open boundary.

References: