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Engineering In-situ Geobarriers for Enhanced Geologic Carbon Storage: A Simulation Study

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Abstract

Geologic carbon storage is a promising technique for mitigating atmospheric carbon emissions. Ensuring long-term sequestration of the injected CO_2 is critical to prevent surface leakage. Challenges exist in selecting an appropriate storage reservoir underlying an impermeable sealing layer. Moreover, controlling injection rates or installing brine producers often face difficulties in efficiency and practicality. To address these limitations, we propose a novel approach to create an in-situ geobarrier through transverse mixing. This technique involves injecting two different brines containing incompatible ions, in this case, Ba^{2+} and SO_4^{2-}, which react to form barite ($BaSO_4$). The resulting barite precipitation will reduce the pore space where the two brines meet along the boundary and decrease the permeability. Eventually, this will effectively act as a barrier which can be utilized as a sealant for subsurface storage. In this study, we conduct reactive transport simulations to evaluate geobarrier formation, followed by CO_2 injection beneath the barrier for storage. Results demonstrate that by controlling injection flow rates and brine concentrations, the geobarrier can be engineered effectively. A well-designed geobarrier ensures safe and sustainable CO_2 storage.

Introduction

Geologic carbon storage has emerged as a critical technology for mitigating atmospheric carbon emissions and combating climate change. Among various approaches to subsurface storage, CO_2 sequestration in underground formations such as saline aquifers and depleted reservoirs holds significant potentials. However, ensuring long-term containment of injected CO_2 is critical, as leakage through permeable pathways or faults could compromise storage integrity and environmental safety. This necessitates the development of innovative solutions that enhance the reliability of CO_2 storage operations.

One promising approach involves intentional creation of an in-situ geobarrier through mineral precipitation. This technique leverages the reaction of injected fluids containing incompatible ions, such as barium (Ba^{2+}) and sulfate (SO_4^{2-}), to form insoluble barite ($BaSO_4$). Barite precipitation reduces the permeability of the pore space, effectively sealing transmissible zones and acting as a hydrodynamic barrier (Fan et al., 2023). Drawing inspiration from challenges in the oil and gas industry—where mineral scale deposition often obstructs flow paths—this approach aims to repurpose such phenomena for geologic carbon storage applications (P.Bedrikovetsky et al., 2011; A.Vaz et al., 2016; Chen et al., 2020). Unlike temporary plugging agents like foams or gels, barite offers exceptional stability and inertness under reservoir conditions, making it a durable solution for mitigating leakage risks (Durucan et al., 2016; Zhu et al., 2021). Preliminary experiments have demonstrated significant reductions in permeability within mixing zones, highlighting the potential of this method to create robust seals at various scales.

This study focuses on assessing the feasibility and effectiveness of barite-based geobarriers for CO_2 storage. By calibrating numerical models against laboratory core flooding experiments, we explore the operational parameters required for the optimal geobarrier shape. Using optimized parameters, numerical simulations are conducted to evaluate trapped amount of injected CO_2. These investigations aim to establish the conditions under which barite precipitation can achieve effective containment and long-term stability. The results of this work underscore the potential of leveraging geochemical processes to enhance the safe and stable geologic carbon storage.

Theory and/or Methods

1. Power law

The reduction in permeability due to barite precipitation can be described by a power law relationship that links porosity and permeability. As barite precipitates within the pore space, it reduces the effective porosity (φ), which in turn decreases the permeability (k) according to the equation as

$$k = k_0(\varphi/\varphi_0)^n$$

where k_0 and φ_0 are the initial permeability and porosity, respectively, and n is an empirical exponent. The value of n depends on the pore structure and the distribution of the precipitate. This relationship captures the nonlinear nature of permeability reduction, emphasizing the effectiveness of barite in blocking flow paths (Lasaga et al., 1994). By quantifying these changes, it becomes possible to predict and optimize the performance of geobarriers in subsurface storage applications.

2. Numerical model

Numerical simulations are conducted on a 2D numerical model with dimensions of 299×299, where each grid block had a length of 6.562 ft, representing an infinite acting reservoir. The model is homogeneous, with a uniform permeability of 100 md and a porosity of 0.2. The grid top is set at a depth of 3,300 ft in a saline aquifer, with a temperature of 120°F and a pressure of 1,400 psi, and the salinity of the aquifer is 50,000 ppm.

The well conditions include two injection wells. The first well injects sodium sulfate (Na_2SO_4) at a concentration of 300,000 ppm, while the second well injects barium chloride ($BaCl_2$) at a concentration of 350,000 ppm. The perforation intervals for the wells are located at coordinates (150, 1, 135) and (150, 1, 165), respectively. Both wells operate at six months - injection rate of 2,200 barrels per day (bbl/day) and two months – post monitoring.

Results

The results of the simulation are presented using two figures and one table, summarizing the outcomes of four scenarios: (a) No barrier, (b) Injection rate ratio of 1:1 between the two injection wells, (c) Injection rate ratio of 4:1 between the two injection wells, and (d) Injection rate ratio of 10:1 between the two injection wells. Figure 1-permeability illustrates the permeability distribution for each scenario, while Figure 1-gas saturation shows the gas saturation results corresponding to each scenario.
The cumulative injected CO_2 sc (ft^3) are as follows: for the "No barrier" scenario (a), it is 1.001×10^8; for the "Injection rate ratio 1:1" scenario (b), it is 0.816×10^8; for the "Injection rate ratio 4:1" scenario (c), it is 1.096×10^8; and for the "Injection rate ratio 10:1" scenario (d), it is 0.725×10^8.

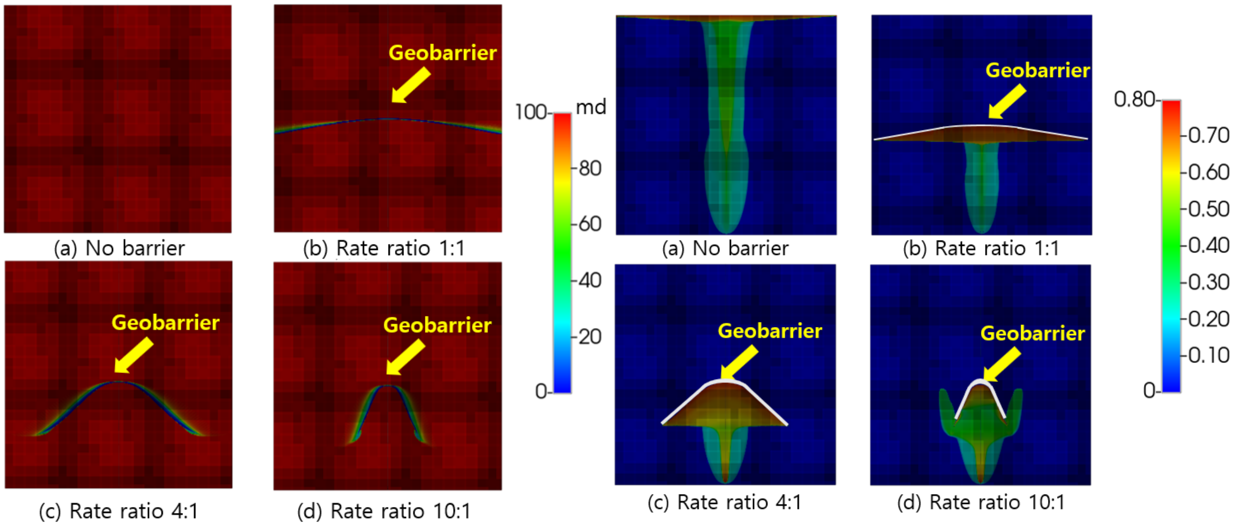

Figure 1. Permeability and Gas saturation at each scenario.

Discussion

The interaction between the two injected fluids results in precipitation, leading to the formation of a geobarrier with significantly reduced permeability. In the affected region, porosity is decreased by 0.0068 due to the barite formation, and permeability is decreased from 100 to 7.23×10^{-6} mD, following a power-law relationship. Additionally, since the injection fluids are denser than the in-situ aquifer fluid, they exhibit a tendency to sink during injection. This behavior leads to the formation of anticline-shaped geobarriers. The shape of the geobarrier varies with the injection rate ratio because the fluid injected at a higher rate propagates more quickly. As a result, the curvature of the geobarrier becomes larger with increasing injection rate ratios, progressing from 1:1 to 10:1.

The gas saturation profiles provide insight into the impact of the geobarrier on geologic carbon storage. In the no barrier case, the injected CO_2 migrates freely upward, spreading toward the aquifer boundary without structural trapping. For the 1:1 injection ratio, the geobarrier creates a complete seal that prevents CO_2 from rising to the upper aquifer. However, the mild curvature of the geobarrier limits the CO_2 storage capacity. The 4:1 injection ratio scenario achieves a balance between sealing and curvature. Although the geobarrier is not entirely sealed, its moderate curvature effectively traps a significant amount of CO_2. In contrast, the 10:1 injection ratio creates a geobarrier with excessive curvature, which results in CO_2 leaking out from the ends of the barrier, reducing its storage efficiency.

The cumulative injected CO_2 reveals that, except for the 4:1 ratio scenario, the no barrier case exhibits a higher injected volume. However, in terms of storage stability, the no-barrier case is less effective, as it lacks a structural trap, relying solely on residual trapping. Consequently, the amount of trapped CO_2 in the no-barrier case is limited. In contrast, the three scenarios with geobarriers securely store most of the injected CO_2 through a combination of structural and residual trapping. Among these, the 4:1 injection ratio scenario is the most effective, safely storing more than five times the amount of CO_2 compared to the no-barrier case.

Conclusions

This study introduces a novel in-situ geobarrier formation technique leveraging transverse mixing of incompatible ions Ba^{2+} and SO_4^{2-} to induce barite precipitation. The barite formation significantly reduces porosity and permeability, creating an effective barrier for subsurface CO_2 storage. Simulation results demonstrate that geobarriers formed under various injection rate scenarios influence CO_2 plume propagation and storage efficiency. The curvature of the geobarrier depends on the injection rate ratio, with higher ratios producing more pronounced curvatures. While the 1:1 injection ratio scenario creates a complete seal, its mild curvature limits storage capacity. The 4:1 injection ratio scenario achieves the most effective balance, storing five times more CO_2 than the no-barrier case while maintaining secure trapping through structural and residual trapping mechanisms. In contrast, the 10:1 injection ratio scenario exhibits excessive curvature, leading to reduced storage efficiency as CO_2 leaks from the barrier's edges.

This study highlights the potential of in-situ geobarrier formation as an innovative and practical solution for enhancing the safety and efficiency of geologic carbon storage. By optimizing injection strategies, such barriers can serve as robust tools for controlling CO_2 plume propagation and maximizing subsurface storage capacity.

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