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Geomechanical Simulation of CO_2 Injection in Fractured Granite Formations at the St John's Dome (SJD): A Dual-Permeability Coupled Modeling Approach

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Abstract

This study investigates how fractured granite reservoirs at the St. John's Dome (SJD) respond to long-term CO_2 injection. Using a dual-permeability geomechanical framework, we evaluate reservoir-scale strain, pressure evolution, and deformation to better understand the storage capacity and stability of crystalline formations.

A fully coupled 3D finite-element geomechanical model was developed, integrating fracture–matrix flow with rock deformation. The granite basement was represented as an elasto-plastic medium governed by the Mohr–Coulomb failure criterion. Boundary conditions accounted for overburden stress, lateral confinement, and hydrostatic pore pressure. CO_2 injection was simulated at 1 MMTPA for 30 years, followed by 50 years of post-injection monitoring. Key outputs included pressure distribution, volumetric strain, surface displacement, and safety margins against failure. Mesh and timestep sensitivity analyses ensured robust and physically consistent results.

Simulations revealed preferential CO_2 migration toward upper most part of the basement, accompanied by widespread compaction-driven deformation. Volumetric strain concentrated around injection wells, while there was not any surface subsidence observed. Pressure increased significantly near injection sites, influencing reservoir stress over time. Trapping analysis indicated that supercritical CO_2 dominated storage, with structural and solubility trapping providing secondary contributions. Overall, geomechanical feedback was found to play a critical role in controlling stress redistribution, deformation, and storage security in crystalline reservoirs.

This work introduces a dual-permeability coupled geomechanical modeling approach for fractured igneous reservoirs, applied to the SJD site. By capturing the interaction between CO_2 migration and stress evolution, the study provides insights into deformation processes and containment reliability in crystalline systems, strengthening confidence in their role as viable long-term CO_2 storage targets.

Introduction

Basement injection storage in crystalline rock formations is a technically challenging but feasible option for long-term geological CO_2 sequestration (Boison, 2024, 2025; I.A. et al. 2013). In contrast to sedimentary basins, granitic rock systems are often characterized by extremely low matrix permeability, preferential flow through fractures, and heterogeneous stress distributions that control pressure propagation (David et al. 2020; Zoback 2010) and ensuring the integrity of storage sites (Bodi et al 2025). These factors complicate our ability to predict fluid migration, pressure buildup, and rock deformation during long-term injection.

Situated on the boundary of New Mexico and Arizona, the St John's Dome (SJD) site has been identified as a potential site for CO_2 storage. However, injection into basement granite induces risks associated with deformation and fault reactivation in the highly fractured reservoir. Previous works indicate that pressure buildup due to fluid injection alters the in situ stress field leading to compaction/subsidence and shear failure at mechanically weak regions (Settari and Walters 2001; Zoback 2010: Yeboah et al 2025).

Reservoir–geomechanical modeling has been demonstrated as the tool of choice to account for the strong feedback between pore pressure evolution and geomechanical deformation within the subsurface (Settari and Walters 2001; Zoback 2010). Here we present a fracture–matrix dual-permeability coupled geomechanical model to simulate fracture–stress redistribution during long-term injection at the SJD site, which is a crystalline system.

Theory and/or Methods

A fully coupled three-dimensional geomechanical model was developed using a dual-permeability framework to represent the fractured granite basement. The matrix and fracture continua were simulated separately to explicitly capture fracture-dominated CO_2 migration while preserving realistic mechanical behavior of the intact rock mass (Settari and Walters 2001).
The granite was modeled as an elasto-plastic medium governed by the Mohr–Coulomb failure criterion. Mechanical properties, including Young's modulus, Poisson's ratio, cohesion, and friction angle, were assigned based on literature values and site-specific constraints (David et al. 2020). Boundary conditions accounted for overburden stress, lateral confinement, and hydrostatic pore pressure.
CO_2 injection was simulated through three vertical wells at a combined rate of 1MMTPA for 30 years, followed by a post-injection monitoring phase. Model outputs included pore pressure distribution, volumetric strain, and surface displacement (subsidence), and safety margins against mechanical failure. Mesh and timestep sensitivity analyses ensured numerical stability.
Figure 1 illustrates the three-dimensional coupled hydrodynamic–geomechanical simulation domain.

Results

CO_2 migration is predominantly fracture-controlled. Pressure buildup is highly localized around injection wells and propagates preferentially along high-permeability fracture corridors, as shown in Figure 2.

Deformation remains relatively distributed as shown Figure 3, with moderate volumetric strain concentrated near injection zones. Surface subsidence is small in magnitude and spatially uniform, indicating limited far-field mechanical disturbance portrayed in Figure 4

Trapping analysis in Figure 5 indicates that supercritical CO_2 dominates storage capacity, with secondary contributions from structural and solubility trapping. Geomechanical feedback significantly influences the spatial distribution of CO_2 and the integrity of the storage system.

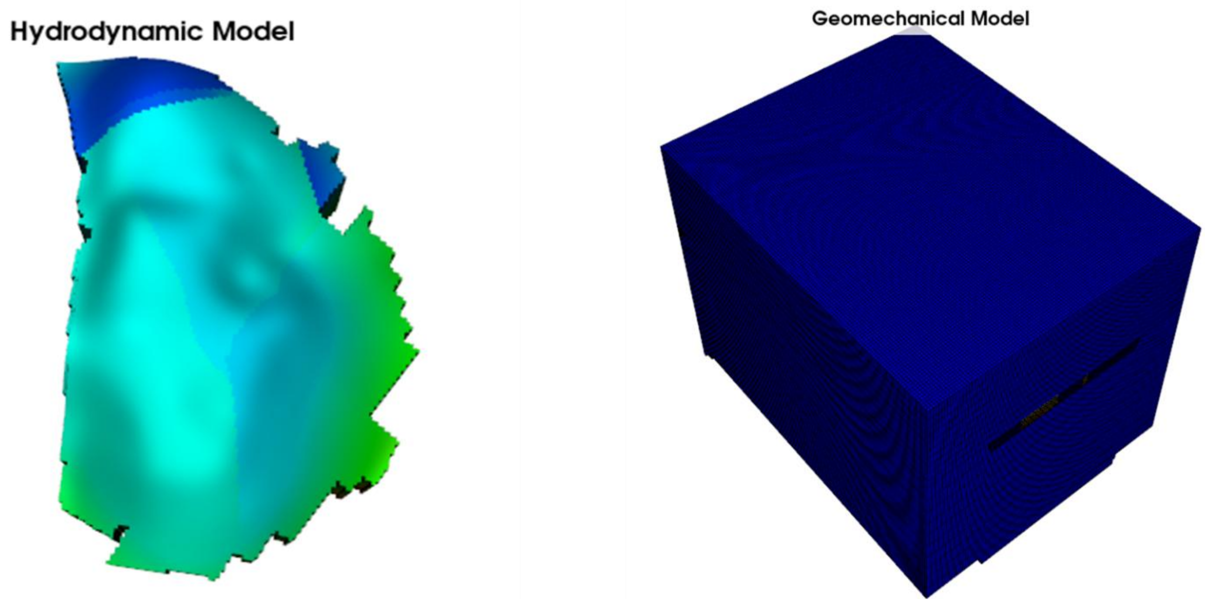

Figure 1. A 3D view of the Hydrodynamic and the Geomechanical Simulation model showing the pressure

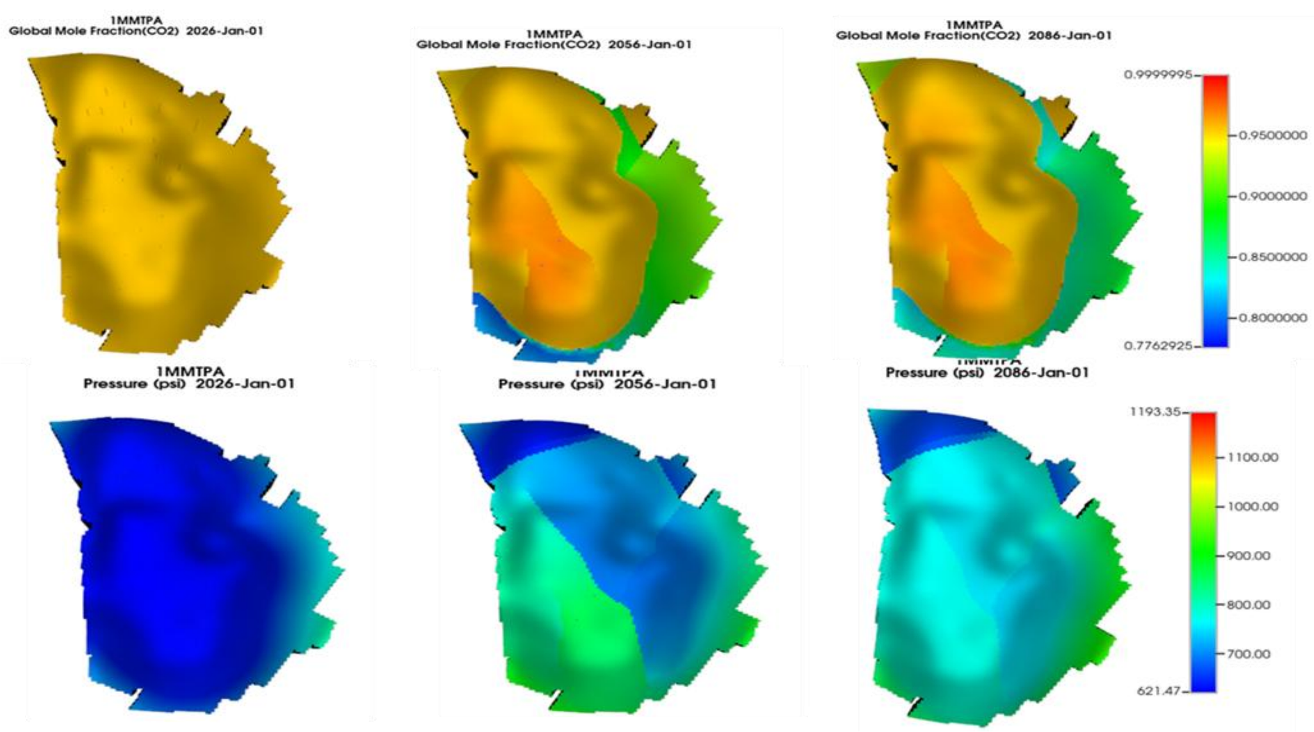

Figure 2. CO_2 Plume with pressure due to Geomechanics at different times of Injection and Monitoring

Discussion

The simulations demonstrate that neglecting geomechanics plays a vital role in analyzing risk in fractured basement reservoirs. While overall pressure buildup and storage capacity are important, critical differences in stress redistribution and strain localization that directly affect containment integrity.

These results underscore the necessity of incorporating geomechanical behavior into site-scale CO_2 storage assessments, particularly in crystalline formations where fractures and faults dominate flow pathways. The dual-permeability framework provides a more realistic representation of fracture–matrix interactions and their geomechanical consequences.

From an operational standpoint, the observed deformation patterns highlight the importance of optimized well placement, injection rate control, and real-time monitoring to CO_2 leakage and induced seismicity risks.

Conclusions

This study presents a coupled dual-permeability geomechanical simulation of CO_2 injection in fractured granite at the St John's Dome site. The results show that:

1. CO_2 migration is strongly fracture-dominated.
2. Pressure buildup and deformation are highly localized near injection wells and along major fracture corridors.
3. Geomechanics adds realism to predictions and allows for conservative risk assessment..

Overall, geomechanical modeling demonstrates the long-term storage security of crystalline reservoirs and supports the suitability of basement targets for CO_2 storage.

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APPENDIX

Measures how much a rock volume changes (expands or contracts) due to stress changes like pressure drop or fluid injection. Negative volumetric strain = compaction (rock volume shrinks). Positive volumetric strain = dilation (rock volume increases).
Important for understanding reservoir deformation, fracture behavior, and storage capacity changes during CO_2 injection.

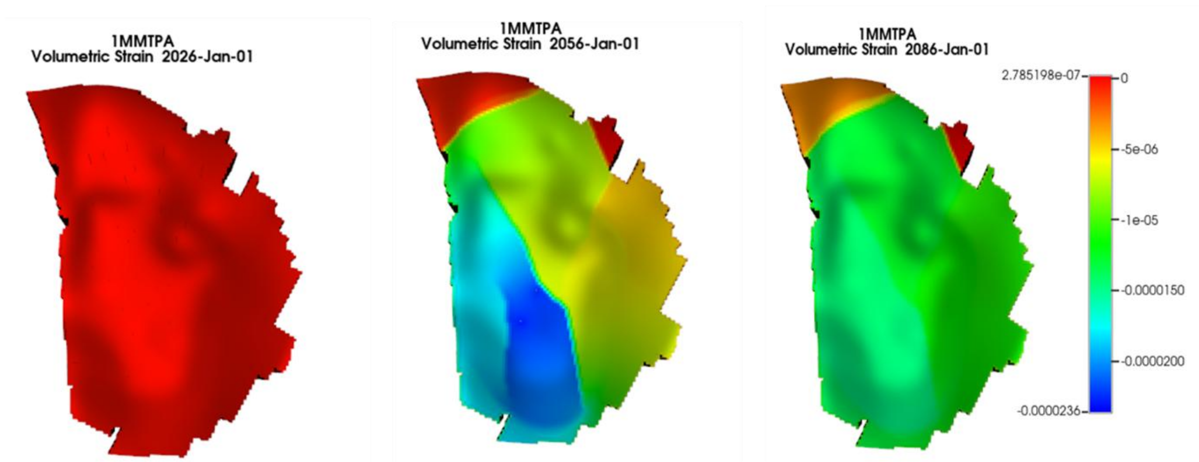

Figure 3. Volumetric Strain due to Geomechanics at different at times of Injection and Monitoring

Refers to the sinking or downward movement of the ground surface caused by compaction of subsurface formations. Often occurs when fluids are withdrawn or pressures change in a reservoir. Negative subsidence signifies sinking and positive subsidence signifies upward movement.
Excessive subsidence can damage surface infrastructure, wells, and cause environmental concerns.

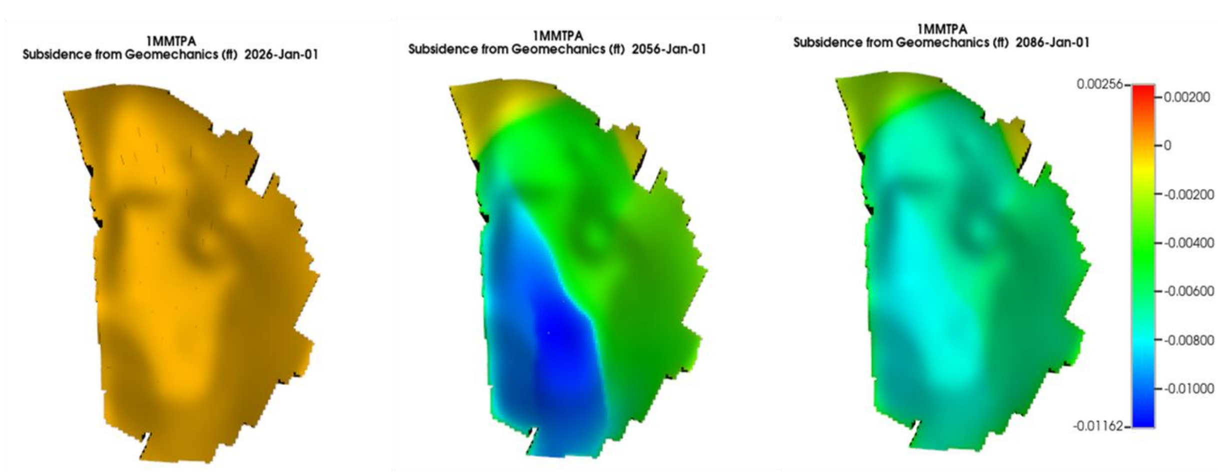

Figure 4. Subsidence from Geomechanics at different at times of Injection and Monitoring

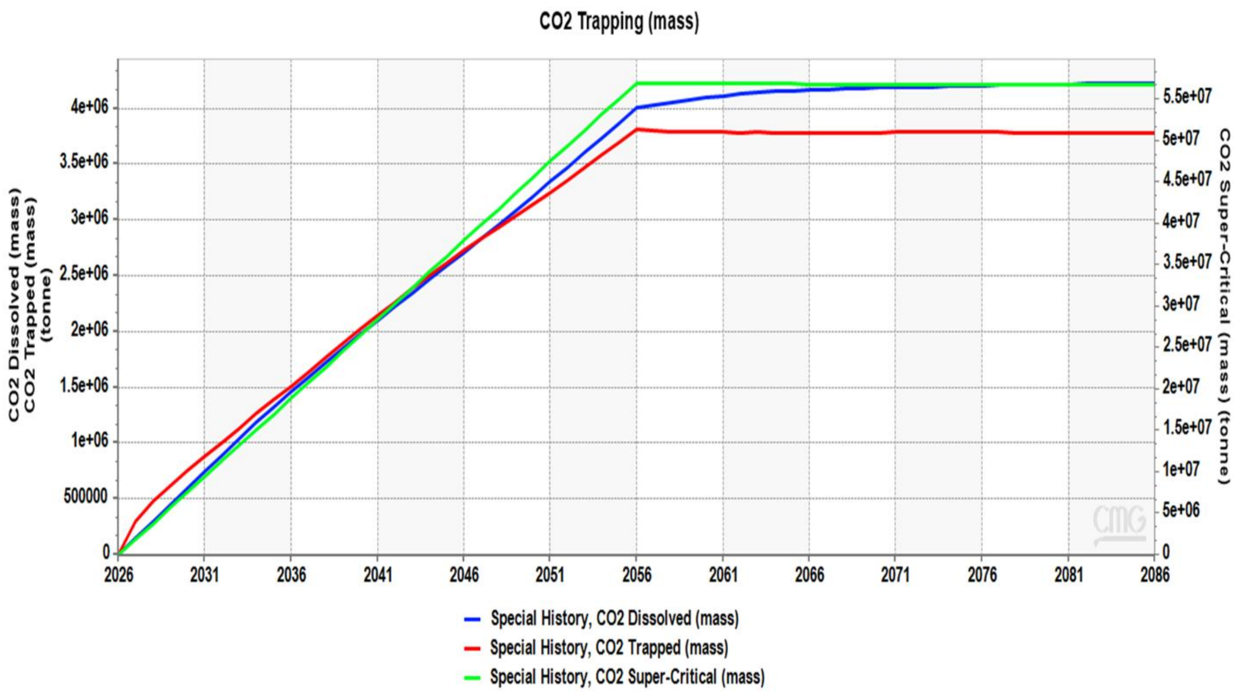

Figure 5ca**.** All the trapping mechanisms present; Structural, Solubility and Supper Critical Trapping