Quantifying Geological Uncertainty for CO_2 Storage in Frontier Basins: A Workflow for Early-Stage Decision Making.

1. Introduction

Large-scale geological storage of carbon dioxide (CO_2) is a key pillar of global decarbonization strategies, with deep saline aquifers representing the most abundant and broadly distributed storage targets (IEA, 2023; IPCC, 2022; Ringrose, et.al., 2021). However, evaluating these formations remains challenging in frontier basins where subsurface data are sparse or unevenly distributed. Limited seismic resolution, incomplete well control, and uncertain petrophysical calibration hinder robust reservoir characterization and introduce significant uncertainty into estimates of injectivity, storage capacity, and containment performance (Ringrose, 2023).

Early-stage assessments nonetheless play a critical role in screening potential storage sites and guiding subsequent data acquisition. Identifying parameters that exert the greatest influence on storage performance enables targeted risk reduction and better-informed investment decisions. In this study, an integrated workflow is presented to quantify geological uncertainties and assess risks associated with CO_2 storage in a large intracratonic sedimentary basin in Saudi Arabia. The approach consists of six steps: (1) subsurface characterization and base-case static modelling, (2) uncertainty and risk assessment, (3) uncertainty-driven sweet spot delineation, (4) detailed analysis of high-risk parameters, (5) scenario-based static and dynamic modelling, and (6) final sweet spot prioritization.

The workflow enables quantification of risked storage capacity, probability of success, and the influence of key geological uncertainties. Results demonstrate how early-stage evaluations can provide actionable insights even when data availability is limited, thereby contributing to more confident and risk-aware site development strategies.

2. Study Area and Data Availability

The study area covers approximately 3,500 km² within an intracratonic sedimentary basin in Saudi Arabia. The basin exhibits laterally extensive siliciclastic and carbonate successions with regionally developed reservoir–seal pairs and long-term structural stability, making it a promising candidate for CO_2 storage.

Subsurface data include 3D seismic coverage and 35 wells, most of which were drilled for hydrocarbon exploration along basin margins. Only a small subset of wells penetrates the target saline aquifer, with five located in a central field originally appraised for deeper Paleozoic intervals. Available data constrain regional stratigraphy, but direct reservoir control, such as core, pressure data, or calibrated petrophysics, is limited. Petrophysical logs offer partial information on porosity and lithofacies yet remain insufficient to fully characterize lateral heterogeneity or seal competence.

The 3D seismic volume provides a robust structural framework but is affected by signal degradation beneath thick carbonate sequences, limiting stratigraphic resolution in the target interval. Thin-unit detection, facies transitions, and subtle changes in seal geometry remain uncertain.

These data limitations typify early-stage CO_2 storage exploration. Reliance on deterministic “best-estimate” models risks underrepresenting subsurface uncertainty. To address this, the present study employs a structured methodology integrating geological characterization, risk classification, and scenario-based modelling to explicitly capture the range of plausible subsurface conditions.

3. Integrated Evaluation Methodology

3.1 Subsurface Characterization and Base-Case Modelling: The target reservoir comprises deltaic sandstones deposited during a low-stand systems tract and overlain by transgressive marine mudstones. Seismic interpretation, well-log analysis, and sequence stratigraphy were integrated to define reservoir geometries, facies, and stacking patterns. A 3D geological model was constructed incorporating lithofacies distribution, porosity, permeability, and net-to-gross. Geomechanical assessment of the sealing unit and overburden was also performed to evaluate containment integrity and ensure compatibility with injection-induced pressure changes.

3.2 Uncertainty and Risk Assessment: The integrated subsurface studies were synthesized to evaluate basin suitability based on storage capacity, injectivity, and containment. The assessment revealed significant contrasts in uncertainty and geological risk across these parameters, highlighting the need for a hierarchical understanding of site-specific challenges.

Reservoir depth and quality were classified as low-risk parameters. The target formation occurs at depths of approximately 2.5–3.2 km, within the pressure–temperature conditions necessary to maintain CO_2 in a supercritical state. Wireline and core data indicate porosities of 15–30% and permeabilities of 400–1000 mD, suggesting favorable injectivity and sufficient pore volume for large-scale CO_2 storage. These parameters are relatively well constrained, with limited uncertainty regarding their impact on overall storage performance.

Moderate-risk parameters included formation water salinity, structural dip, seal thickness, and lateral continuity, reflecting limited data coverage and potential lateral heterogeneity. Salinity varies from over 10,000 to ~30,000 mg/L, structural dip ranges from 0.5°–7°, and seal thickness and continuity span 100–160 ft.

The highest-risk parameters were seal lithology and facies heterogeneity, which strongly influenced long-term containment but remain poorly constrained. Spatial variability ranges from carbonate mudstone–shale in the east and north to alternating sandstone–shale in the west and southwest, with corresponding differences in seal quality. This risk classification indicated that while reservoir properties are favorable, seal characteristics dominate the uncertainty and represent the principal containment risk for the system.

3.3 Uncertainty-Driven Sweet Spot Delineation: To focus on subsequent analyses and reduce overall geological uncertainty, medium-risk parameters, including structural dip, formation water salinity, and seal thickness, were integrated to delineate spatially contiguous zones exhibiting favorable storage conditions. These parameters were incorporated into a multi-criteria geospatial framework that enabled the superposition of depth, structural, reservoir quality, and seal-thickness layers. The resulting composite risk surface was normalized to generate a Cumulative Geological Risk Index (CGRI), which served as the basis for identifying the most prospective sector of the basin, herein referred to as the CO_2 storage sweet spot.

The delineated sweet spot represents the area characterized by the lowest cumulative geological risk, combining adequate reservoir thickness and porosity with a laterally continuous, relatively thick sealing interval. This zone was selected for higher-resolution evaluation to further assess the remaining high-risk parameters, primarily seal lithology and lateral facies variability.

3.4. Detailed Risks Evaluation within the Sweet Spot: A detailed assessment of high-risk parameters, particularly seal lithology and facies heterogeneity, indicated a moderate but manageable containment risk. This risk is primarily associated with lateral facies transitions and variability in shale thickness within the sealing interval. The seal unit comprises predominantly low-permeability carbonate mudstones interbedded with shales of variable thickness. The cumulative shale thickness within the primary sealing package ranges from approximately 40 to 90 ft within a total stratigraphic interval of about 150 ft. Although these characteristics suggest an effective top seal, the spatial variability in shale proportion and lithologic alternation introduces uncertainty regarding lateral seal continuity.

Sedimentological and facies analysis indicated that the depositional system evolved through a marine transgressive phase followed by high-stand conditions, resulting in a pronounced west-to-east facies transition. The western sector is dominated by sand-prone facies, whereas the eastern sector is characterized by more carbonate-rich deposits. Due to limited well control, these lateral facies variations remain only partially constrained, introducing additional uncertainty in the detailed characterization of both the reservoir and sealing formations (Figure 1).

3.5 Scenario-Based Static and Dynamic Modelling

3.5.1 Static Scenarios: Three conceptual caprock scenarios were built to represent the plausible range of sealing behavior:

1. **Shale-dominated seal:** thick, continuous, low-permeability shale with strong containment.
2. **Limestone-dominated seal:** moderate permeability due to facies mixing and micro-fracturing.
3. **Sandstone-influenced seal:** thin, partially discontinuous sealing layers with localized vertical communication potential.

Reservoir properties were held constant across scenarios to isolate the effects of caprock variability. Petrophysical inputs were derived from analogs and available logs; seal permeability and lithology were adjusted per scenario. Seal thickness ranged from 120–160 ft, consistent with observed variability.

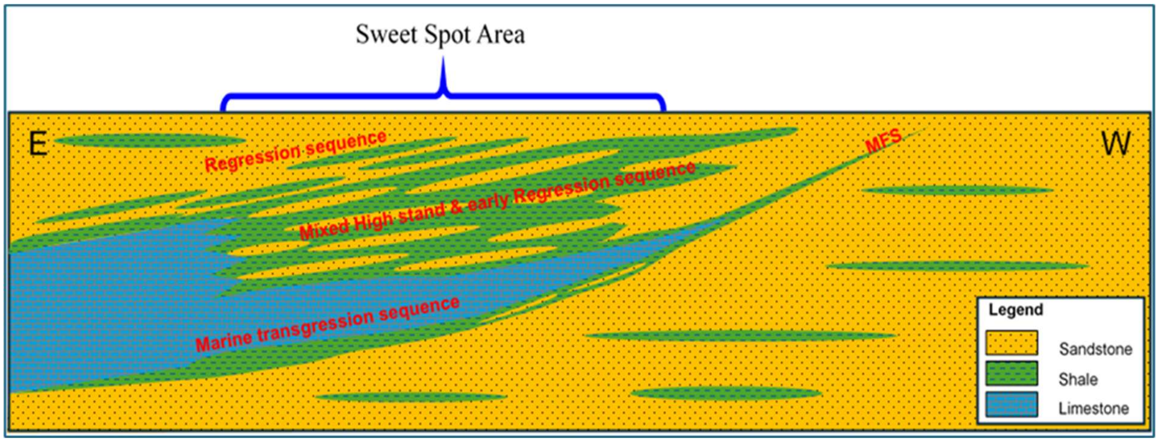

Figure 1: Basecase schematic cross-section of study area. Alternate scenarios included variable proportion and continuity of shales, sandstone and limestone in sweet spot seal area.

3.5.2 Dynamic Simulations: Dynamic models were generated using a compositional simulator with a horizontal grid resolution of 200 × 200 m and vertical layering of ~7 ft. A maximum operational pressure gradient of 0.8 psi/ft was applied. Simulations included 25 years of injection followed by 1,000 years of post-injection evolution. Key performance metrics included containment efficiency, pressure buildup, plume migration, and effective storage capacity. The results are given below:

- **Scenario 1 (Shale-dominated):** full containment, minimal vertical communication, narrow pressure footprint, and strong long-term trapping.
- **Scenario 2 (Limestone-dominated):** limited upward pressure transfer and slightly increased plume height, but no leakage (Figure 2).
- **Scenario 3 (Sandstone-influenced):** pressure communication and limited CO_2 fluxes, but no failure; broader plume footprint requiring enhanced pressure management (Figure 3).

Across all cases, dynamic behavior remained within safe operational limits, though sensitivity to seal heterogeneity was clear.

4. Conclusions and Implications

This study demonstrates a practical workflow for evaluating CO_2 storage in data-limited basins by integrating geological characterization, risk-based classification, and scenario modelling. Key outcomes include:

- A structured, multi-parameter risk classification framework applicable to frontier storage settings.
- Clear delineation of low-risk sweet spots to prioritize appraisal and reduce exploration costs.
- Quantification of how uncertainties in seal lithology and heterogeneity propagate into storage performance.
- Scenario-based predictions demonstrate robust containment under a range of plausible conditions, while highlighting areas requiring targeted data acquisition and monitoring.

The methodology provides a transparent, defensible basis for early-stage CO_2 storage decisions and can be readily transferred to other underexplored basins. As CO_2 storage deployment scales globally, such uncertainty-explicit workflows will be essential to ensure safe, efficient, and bankable project development.

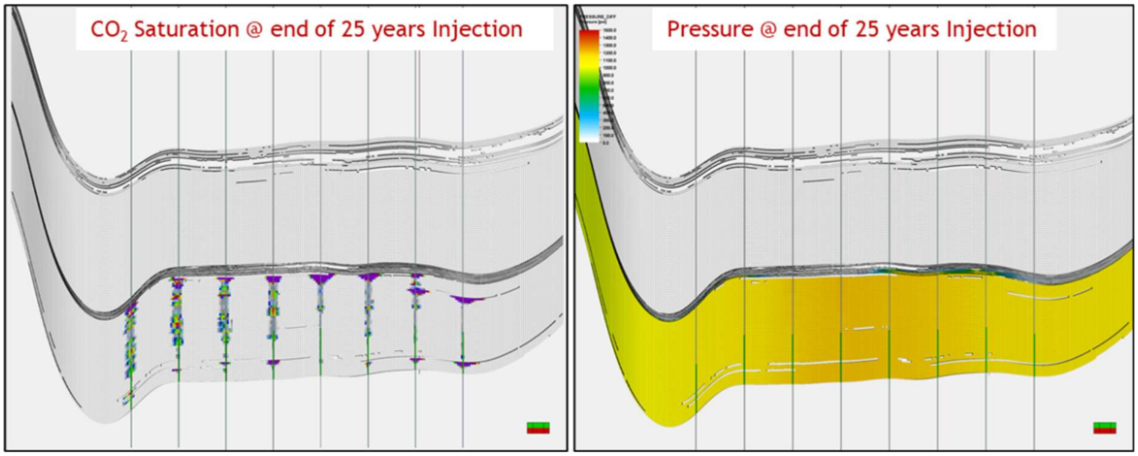

Figure 2: Limestone dominated scenario simulation results showing limited plume height and pressure leakage.

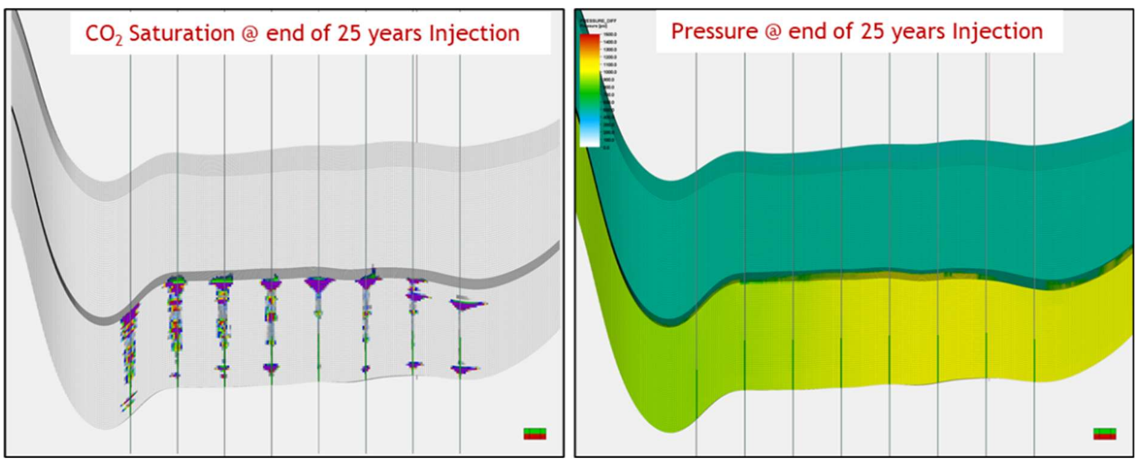

Figure 3: Sandstone dominated scenario simulation results showing slightly increased plume height

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