Analogue-Based Multi-Scenario Modelling for Assessing CO_2 Storage Potential in Data-Poor Carbonate Saline Aquifers

Introduction

Carbon Capture and Storage (CCS) is widely regarded as a key technology for mitigating anthropogenic greenhouse gas emissions. Robust geological modelling of potential storage sites is essential for reliable estimation of pore volume and storage capacity, as well as for forecasting CO_2 plume migration, pressure evolution, and leakage risk. A substantial proportion of global carbon storage capacity is hosted in gently dipping saline aquifers with limited subsurface data. In such data-poor settings—particularly those involving complex carbonate systems—conventional geostatistical and stochastic modelling approaches often fail to adequately capture geological uncertainty. Carbonate reservoirs are characterized by complex pore systems and strong heterogeneity driven by depositional architecture and diagenetic overprinting, which typically require extensive core, image log, or permeability data to constrain. In the absence of such data, innovative geomodelling approaches are needed to generate reliable static models for carbon storage assessment.

This study presents a novel analogue-based, multi-scenario geomodelling approach designed to address these challenges in data-poor carbonate saline aquifers. The methodology is tested using a case study from Saudi Arabia. The workflow integrates regional geological knowledge and analogues from nearby data-rich areas to construct conceptual depositional models. Key sedimentological and petrophysical parameters are systematically varied to generate multiple plausible static models, allowing uncertainty in storage capacity and injectivity to be explicitly quantified.

Geological Setting

The study area comprises a large, gently dipping (<1°) carbonate saline aquifer located in Saudi Arabia. Available subsurface data are limited to 2D seismic coverage and approximately 20 offset wells. The target storage complex consists of a carbonate saline aquifer overlain by a dense limestone seal. The storage aquifer was deposited during the Barremian in a low-angle carbonate ramp system and comprises two transgressive–regressive cycles, with the most favorable reservoir facies developed during highstand system tracts. The highstand succession is characterized by a shoaling-upward sequence, transitioning from low-energy middle-ramp mudstones and wackestones to moderate- to high-energy inner-ramp grainstones and floatstones. The transgressive system tract consists predominantly of dense, argillaceous limestones deposited in a clay-prone inner-ramp setting, forming both an intraformational seal and the regional top seal for the storage aquifer (Jeong et al., 2017). Within the highstand inner-ramp setting, rudist complexes are developed, where rudist-rich shoal deposits grade laterally into peloidal packstone–grainstone intershoal facies (Al-Ghamdi, 2013). Nevertheless, the dimensions and lateral extent of these complexes, as well as their lateral and vertical connectivity remain poorly constrained. However, reservoir pressure data indicate minor permeability variations within an overall lateral hydraulic connected reservoir across several kilometers, suggesting a laterally continuous reservoir system in the area of interest.

Modelling Methodology

This study adopts an analogue-based, multi-scenario geomodelling strategy that integrates depositional concepts with uncertainties related to sedimentological heterogeneity, diagenesis, and petrophysical properties. The objective is to capture a realistic range of geological outcomes for carbon storage assessment.

Depositional Concept Development: The workflow begins with the development of a conceptual depositional model using analogues from nearby data-rich carbonate systems, supplemented by offset well data. Key geological uncertainties are identified, including the dimensions, geometry, and connectivity of rudist complexes; facies assemblages and proportions; and the impact of diagenesis on porosity and permeability. These uncertainties exert strong controls on both facies and petrophysical models. To systematically capture this uncertainty, a set of key modelling parameters is defined (Table 1), including facies variogram ranges, facies proportions and boundaries, and porosity–depth relationships. Each parameter is assigned low-, base-, and high-case values, providing a structured framework for scenario generation.

Scenario-Based Modelling: A structural framework is constructed using interpreted depth maps derived from 2D seismic data. Multiple facies model scenarios are then generated using a three-level fractional factorial experimental design, in which each parameter can take low, base, or high values (Box et al., 1978; Jackson et al., 2022). This approach allows systematic evaluation of the influence of individual parameters and their interactions on the resulting geomodels. Core analysis and injectivity test data from offset wells are used to define alternative porosity–depth trends and porosity–permeability transforms for each facies, accounting for compaction and diagenetic effects. Multiple porosity and permeability realizations are subsequently generated to represent a range of plausible petrophysical scenarios.

Model Validation and Uncertainty Quantification: All generated models are validated against the underlying geological concepts, available well data, and injectivity test results. The validated models are then used to estimate ranges of pore volume, CO_2 storage capacity, and injectivity, explicitly capturing uncertainty associated with sedimentological heterogeneity and petrophysical variability. Comparative analysis of the multiple models provides insight into the sensitivity of storage capacity and flow behavior to geological uncertainty.

Parameters	Low Case	Base Case	High Case
GDE boundary	Proximal inner ramp (PIR) boundary close to Well A	PIR boundary between Well A and B	PIR boundary close to Well B
Facies proportion (FA1/FA2/FA3) *	0.1/0.4/0.5	0.2/0.3/0.5	0.3/0.3/0.4
Facies variogram (major/minor)	6 km/5 km	12 km/10 km	18 km/15 km
Facies trend map	Ave. 10% FA1 in prospect area	Ave. 15% FA1 in prospect area	Ave. 20% FA1 in prospect area
Porosity-depth trend	High gradient	Moderate gradient	Low gradient
Permeability transform	P90	P50	P10

Table 1 *Summary of investigated factors controlling sedimentological heterogeneities, petrophysical properties and volumetric calculations, and their low,* medium *and high settings in this study. * FA1: High-to-moderate Energy Inner Ramp (IR) Granstone/Rudstone; FA2: Moderate to low Energy IR Packstone/Wackstone; FA3: Low Energy Middle Ramp (MD) Mudstone/Wackstone.*

Results

Multiple geological models were constructed to represent a range of plausible facies distributions and petrophysical properties (Figure 1). The facies models show significant variability in the size, geometry, and connectivity of rudist-rich complexes, which exert a strong control on CO_2 migration and storage behavior. Porosity models display relatively consistent values in shallow intervals across different facies, reflecting the presence of abundant microporosity even in tighter carbonate lithologies. In contrast, porosity distributions in deeper intervals are highly sensitive to assumed compaction trends, resulting in significant uncertainty related to burial depth and diagenetic porosity reduction. Permeability models reflect compounded uncertainties from facies architecture, porosity distributions, and porosity–permeability transforms. Facies distribution is the dominant control on permeability in shallow areas, whereas permeability is substantially reduced in deeper intervals due to lower porosity.

Across the realized models, the estimated pore volume of the mapped prospect area ranges from 42 to 48 billion m^3, with a mean value of approximately 45 billion m^3. Corresponding CO_2 storage capacity estimates range from 0.2 to 1.3 Gt, assuming storage efficiencies between 1% and 5%. A significant discrepancy in permeability among the models leads to substantial uncertainties in the spatial distribution of injectivity (kh). Nevertheless, the results generally indicate the presence of shallow, high-potential 'sweet spots' characterized by a higher likelihood of grainstone and rudstone development, which are associated with superior reservoir quality, representing priority targets for future exploration and injection planning.

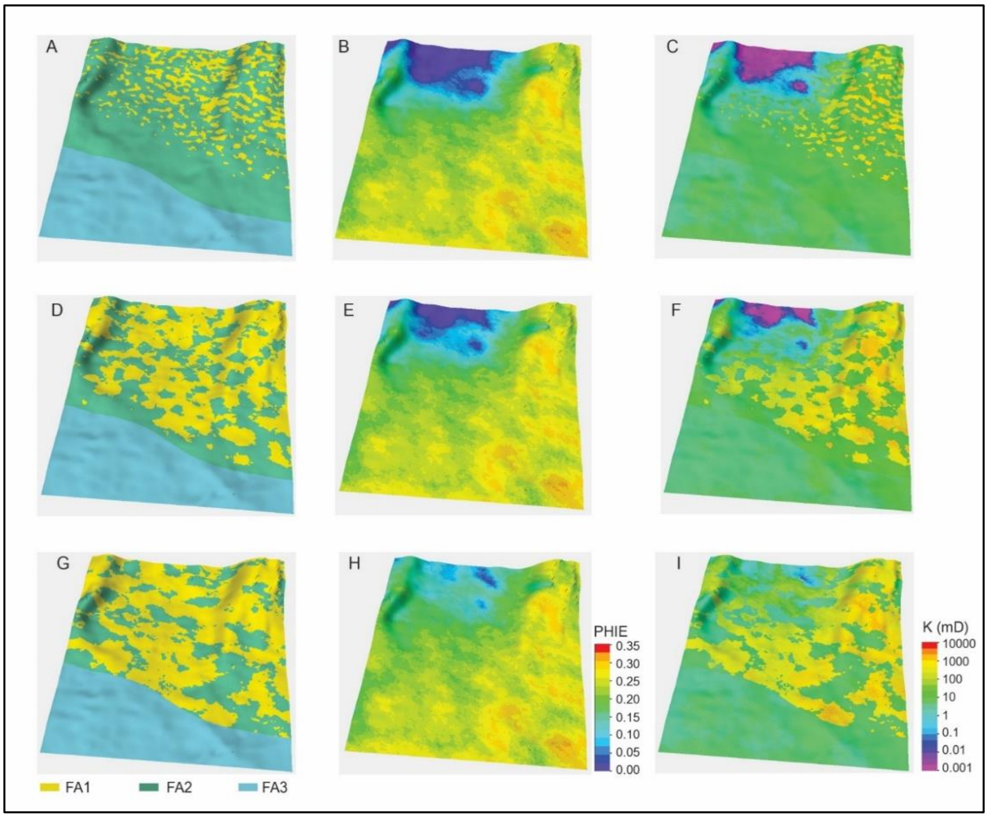

***Figure 1** 3D perspective views of selected models, illustrating contrasting facies distribution (A, D, G) and resulting porosity (B, E, H) and permeability distribution (C, F, I).*

Conclusion

This study presents a scenario-based, analogue-driven geomodelling approach for quantifying geological uncertainty in complex carbonate saline aquifers with limited subsurface data. Application of the methodology to a gently dipping ramp carbonate system in Saudi Arabia demonstrates its effectiveness in capturing uncertainty related to facies architecture, petrophysical properties, storage capacity, and injectivity. By generating multiple plausible geological models through systematic parameter variation, the approach provides robust estimates of pore volume and CO_2 storage capacity, and injectivity, and supports informed decision-making for site selection and future data acquisition. The methodology offers a practical framework for reducing risk in early-stage CCS projects in data-poor carbonate settings. Future work should focus on improved representation of diagenetic processes, including dissolution, cementation, and fracturing, to further refine storage performance predictions.

References

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