Dynamic simulation of migration-assisted gigatonne-scale CO_2 storage, offshore Australia

Migration-assisted trapping in regionally extensive saline aquifers is increasingly recognised as a viable mechanism for secure geological CO_2 storage at the gigatonne scale required for industrial decarbonisation (Ringrose et al., 2021; Bump et al., 2023). In such systems, injected CO_2 migrates up-dip under buoyancy and becomes immobilised through a combination of residual trapping, capillary trapping behind intra-aquifer heterogeneities, and dissolution into formation brine. Demonstrating that the injected CO_2 remains contained within the storage complex over timescales of thousands of years is a key regulatory requirement and typically necessitates dynamic simulation.

This paper presents a regional-scale dynamic simulation study of the G-14-AP permit in the Browse Basin, offshore Australia. The study demonstrates the viability of migration-assisted trapping, quantifies plume migration distances, and estimates pressure-limited storage capacity. The efficacy, relative contribution and key controls on the different trapping mechanisms are examined and quantified. The work addresses several challenges that distinguish saline aquifer CO_2 storage from conventional hydrocarbon reservoir simulation, including construction of a regional static model from relatively sparse well control, parameterisation of buoyancy-dominated multiphase flow in which capillary effects are critical, and assessment of pressure limits in an aquifer that extends across a large depth range.

Particular emphasis is placed on the role of capillary heterogeneity in controlling plume migration and trapping efficiency. This study demonstrates how available core, log and analogue data can be integrated into a dynamic modelling workflow to support storage assessment in a data-sparse settings that often characterise saline aquifers when compared with storage in depleted hydrocarbon fields.

Geological setting and storage concept

The G-14-AP licence covers approximately 9,500 km² in the Browse Basin, offshore north-west Australia, and has the potential to be a major storage hub for Australian and regional CO_2 emissions. The project targets Jurassic saline aquifers within the Plover and Lower Vulcan Formations. These aquifers are sealed by shales of the Upper Vulcan Formation and overlain by thick Cretaceous marine shales of the Echuca Shoals and Jamieson Formations.

The proposed storage complex lies east of the Barcoo Sub-Basin margin on the Leveque Shelf (Figure 1), where the Jurassic section forms a gently dipping (approximately 1.5^o), largely unfaulted monocline rising to the south-east (Figure 2). This configuration is favourable for migration-assisted trapping, with CO_2 injected into thicker, deeper sands on the down-dip side of the licence and subsequently migrating up-dip under buoyancy through well developed heterogeneous aquifers.

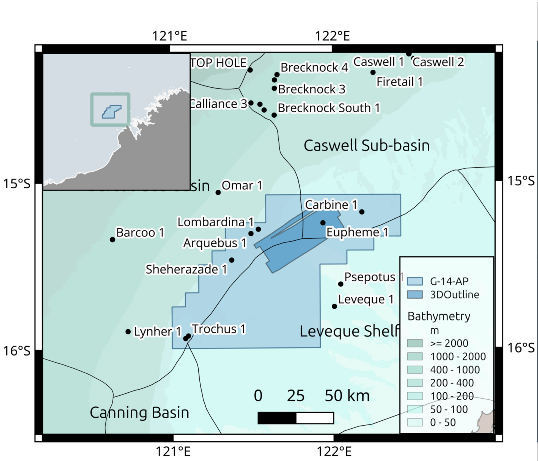

Figure 1 *Location map*

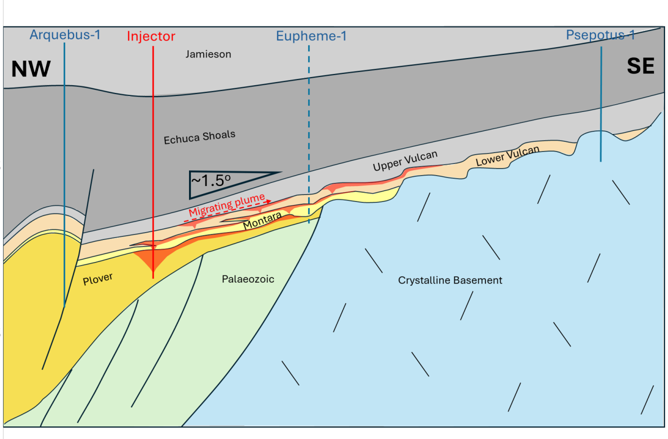

Figure 2 *Structural and stratigraphic setting*

The Plover Formation comprises thick, laterally extensive fluvio-deltaic sandstones, while the Lower

Vulcan Formation includes both a relatively homogeneous, sand-prone, forced regressive unit (the Montara Member) with more heterogeneous coastal deposits above. This stratigraphic stacking pattern, which includes considerable vertical and lateral permeability and capillary heterogeneity, is expected to positively influence CO_2 migration pathways and trapping behaviour.

While no wells penetrate the proposed storage complex, 7 wells in the permit supplemented by a further 10 in the surrounding area provide sufficient core, log and test data to robustly constrain aquifer properties and facies architecture.

Static model construction

A regional static model was constructed covering the full licence area to capture both injection-scale and migration-scale processes.

Depth structure was derived primarily from interpretation of sparse 2D seismic data supplimented locally by a 1,000 km^2 3D seismic survey that enabled more detailed definition of aquifer topography. Aquifer properties were extrapolated away from wells using trends derived from petrophysical analysis, geological interpretation, and informed by analogues. A sequence stratigraphic framework was developed to distinguish the relatively homogeneous, high net-to-gross sands of the Montara Member from the more heterogeneous fluvio-deltaic Plover Formation below and the lower-quality coastal deposits of the upper Lower Vulcan Formation. These units are expected to exhibit distinct flow and trapping behaviour.

Heterogeneity was incorporated through facies-based modelling, with each facies assigned characteristic porosity-permeability and capillary relationships. Facies proportions were constrained by well logs and stratigraphic interpretation, with lateral variation guided by geological trends and seismic attributes where available.

Porosity was modelled as a function of depth per facies to account for compaction across the large depth range of the aquifer (1,500 m). Permeability distributions were constrained using extensive core data from the nearby Calliance field, where petrographic analysis, grain size distributions and log character indicate similar depositional environments, detrital compositions and diagetic history between the Plover and Montara of Calliance and the G-14-AP licence.

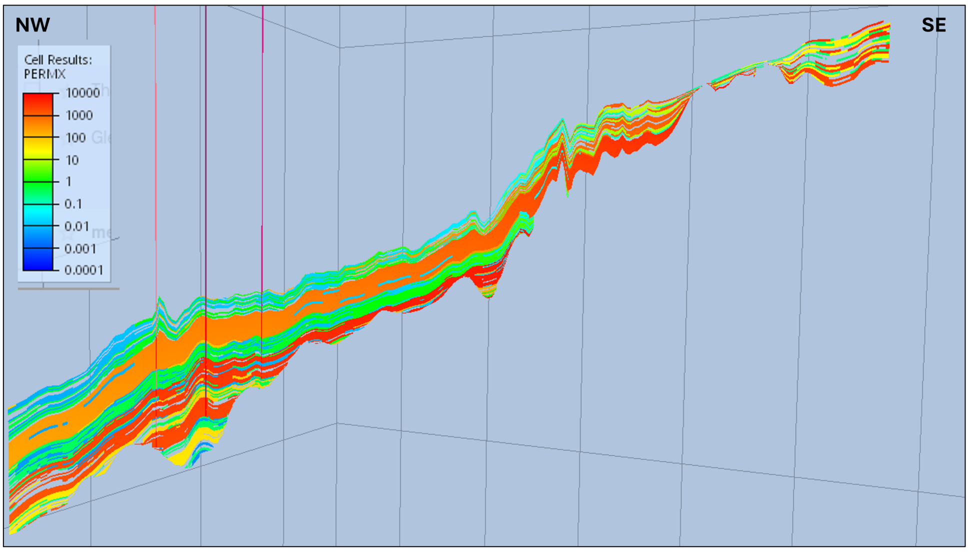

Figure 3 *Dip section through model showing permeability*

Multiple geological scenarios were generated by varying facies proportions and permeability trends within ranges consistent with the data.

Dynamic simulation approach

Dynamic simulations were performed using OpenGoSim Cirrus to model CO_2 injection, migration, and long-term trapping behaviour. Multiphase flow physics included buoyancy, capillary pressure, relative permeability hysteresis, and dissolution of CO_2 into formation brine. Dynamic thermal effects were neglected.

Dynamic parameters were selected based on published literature (Burnside and Naylor, 2014; Ebeltoft et al., 2025) and special core analysis (SCAL) data from the Calliance field, including capillary pressure measurements and residual gas saturation data. Imbibition residual gas saturation was informed by the Calliance data, which indicate lower values than commonly assumed in the literature. Capillary heterogeneity was incorporated by assigning facies-specific CO_2-brine capillary pressure curves scaled from Calliance N_2-brine data to equivalent facies in the static model. This allowed capillary entry pressures and trapping behaviour to vary spatially in accordance with geological heterogeneity.

Injection scenarios included single wells and clusters of wells around a single surface location. Bottom-hole pressures were constrained to remain below the modelled fracture pressure of the sealing units. Injection rates were limited to a maximum of 6 Mtpa per cluster, resulting in a maximum injected volume of 150 Mt over a 25-year injection period for individual development scenarios. Initial simulations were run for up to 3,000 years to assess long-term plume evolution, demonstrating that plume migration stabilised by approximately 1,000 years. Subsequent sensitivity studies were therefore run over this timeframe. Geological, dynamic, and operational parameters were varied to identify the key controls on plume migration distance and storage security.

Additional simulations examined a full-licence development scenario with six injection clusters brought on-line sequentially at five-year intervals. These simulations incorporated connected pore volume outside the licence area using analytical aquifer representations and included sensitivities on aquifer permeability. Due to limited definition of aquifer topography beyond the 3D seismic extent and computational constraints, these full-licence simulations focused on injection-period pressure behaviour rather than long-term plume migration.

Results

Dynamic simulations indicate that CO_2 plume migration is largely stabilised within approximately 1,000 years after injection, with only limited additional up-dip movement thereafter. By this time, only a very small fraction (<2%) of the injected CO_2 remains mobile. Approximately one-third of the injected volume is residually trapped, one-third is immobilised beneath or behind capillary barriers, and one-third is dissolved in formation brine. With increasing time, dissolution continues at the expense of the other trapping mechanisms (Figure 4).

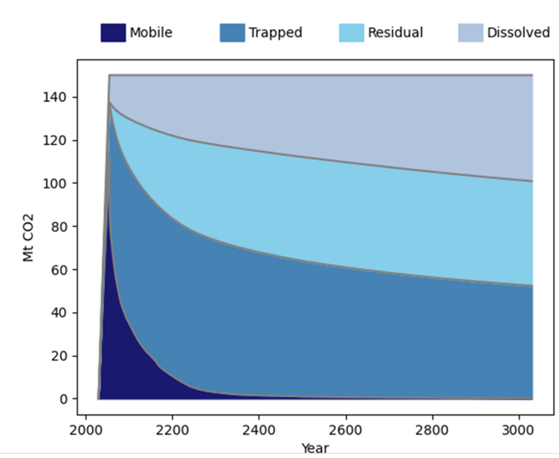

***Figure 4** CO_2 fate*

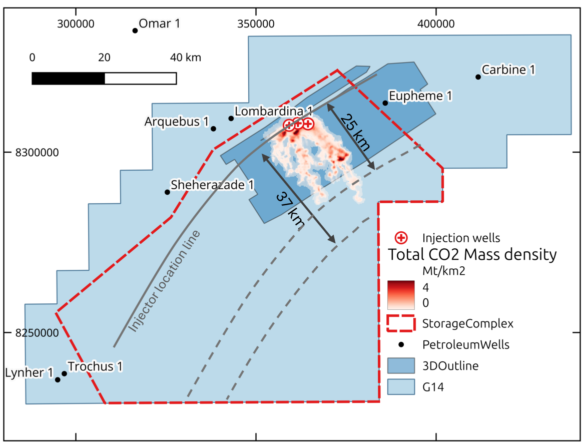

***Figure 5** Modelled plume 1000 years after 150 Mt CO_2 injection*

These results highlight the importance of explicitly representing capillary heterogeneity in regional-scale models. In this study, heterogeneity was represented at the grid-cell scale without upscaling; incorporation of finer-scale heterogeneity would be expected to further enhance capillary trapping.

For scenarios that injected a total 150 Mt of CO_2, simulated plume migration distances ranged from approximately 25 to 37 km up-dip from the injection point (Figure 5). The primary controls on migration distance were the assumed residual gas saturation and the detailed aquifer topography up-dip of the injection location, which could either focus or disperse flow pathways. Migration distance was relatively insensitive to the absolute magnitude of capillary pressure, provided that capillary heterogeneity was represented. 150 Mt of injected CO_2 is modelled to remain securely within the licence area for 1000 years except in extreme geological scenarios for specific areas where the distance to the up-dip licence boundary is shorter. In such cases migration risk can be mitigated through reduced injection volumes or alternative well placement, ensuring the plume is retained in the permit area and the CO_2 sequestration is robust.

Full-licence multi-injection cluster simulations indicate that 550–1400 Mt of CO_2 could be injected without exceeding fracture pressure constraints. Owing to the high quality and lateral connectivity of the aquifer, pressure dissipates rapidly away from injection centres. Consequently, the pressure limit is reached not at the injection wells but at the shallower up-dip extent of the aquifer, where the reduced depth results in a narrower margin between initial pore pressure and fracture pressure.

Conclusions

Dynamic simulation of the G-14-AP licence demonstrates that migration-assisted trapping is a viable mechanism for gigatonne-scale CO_2 storage. Explicit representation of capillary heterogeneity and residual gas trapping is critical to predicting plume migration and long-term containment. Aquifer topography and depth-dependent pressure limits exert strong controls on both plume behaviour and storage capacity, underscoring the need for regional-scale modelling.

Given data sparsity, common for saline aquifer storage, simulation is performed on regional-scale models rather than well-constrained development models. Scenario-based approaches, careful trend analysis, and use of analogue data are therefore essential to characterise uncertainty and support robust decision-making.

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