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Capillary Pinning and the Role of Sedimentological Heterogeneity in CO₂ Storage

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Summary

The North Sea's potential as a Green Energy Hub depends on large-scale CO₂ storage in shallow-marine sandstones, but the effects of geologic heterogeneity, such as permeability barriers and capillary entry pressure contrasts, remain underexplored. This study uses multiphase flow simulations on geologically realistic, surface-based reservoir models informed by outcrop analogue data from wave-dominated shoreface sandstones. We investigate how sedimentological heterogeneity influences CO₂ plume migration, pressure evolution, and storage capacity.

Preliminary results show that capillary barriers tied to facies architecture and early cementation, conditioned to clinoform geometries, significantly control plume movement. These barriers promote lateral spreading and residual trapping, representing a potential upper limit on long-term CO₂ storage when stable. Clinoform-related heterogeneity also induces flow compartmentalization, limiting pressure dissipation and enhancing anisotropy, which may reduce injectivity and cause spatially variable pressure buildup.

Comparisons with waterflood simulations reveal contrasting dynamics: water advances more uniformly, while CO₂ migration is more sensitive to fine-scale architecture due to its lower interfacial tension and capillary entry pressures. These findings underscore the need to incorporate realistic sedimentological heterogeneity in dynamic models to avoid misestimating injectivity, pressure behavior, and storage security. This approach offers a robust framework for early-stage screening and risk assessment in complex storage settings.

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Introduction

Capillary pinning, also known as local capillary trapping, refers to the immobilization of CO₂ at capillary barriers where the upward buoyant pressure of the migrating plume is insufficient to overcome the capillary entry pressure of overlying pore throats (Figure 1). This mechanism, which has been proposed as a fifth geologic CO₂ trapping process, alongside structural, solubility, residual, and mineral trapping, may play a critical role in determining the efficiency, injectivity, and security of subsurface carbon storage (Zhang et al., 2025).

Despite its importance, capillary pinning remains underrepresented in many reservoir modeling frameworks. The terminology surrounding it is often inconsistent or conflated with residual and hysteresis trapping, leading to confusion and its frequent omission from reservoir-scale simulations. Furthermore, accurately characterizing and upscaling the geological heterogeneities that give rise to capillary barriers presents a persistent challenge. As a result, reported estimates of CO₂ immobilized via capillary pinning vary widely, from as little as 3% to as much as 100% of total “trapped CO₂”, highlighting the need for better integration of this mechanism into both conceptual and numerical models.

Alongside our literature review (Zhang et al., 2025), this modeling study aims to bridge the gap between the reservoir engineering community, which is well-versed in hydrocarbon recovery but needing adaptations for CCS, and the subsurface storage community, which often lacks access to and thus understanding of relevant petroleum-based literature. We synthesize fundamental concepts, experimental insights, and state-of-the-art modeling strategies that address capillary pinning from published work, while also presenting new results from dynamic reservoir simulations that illustrate the practical implications of this mechanism in geologically realistic settings.

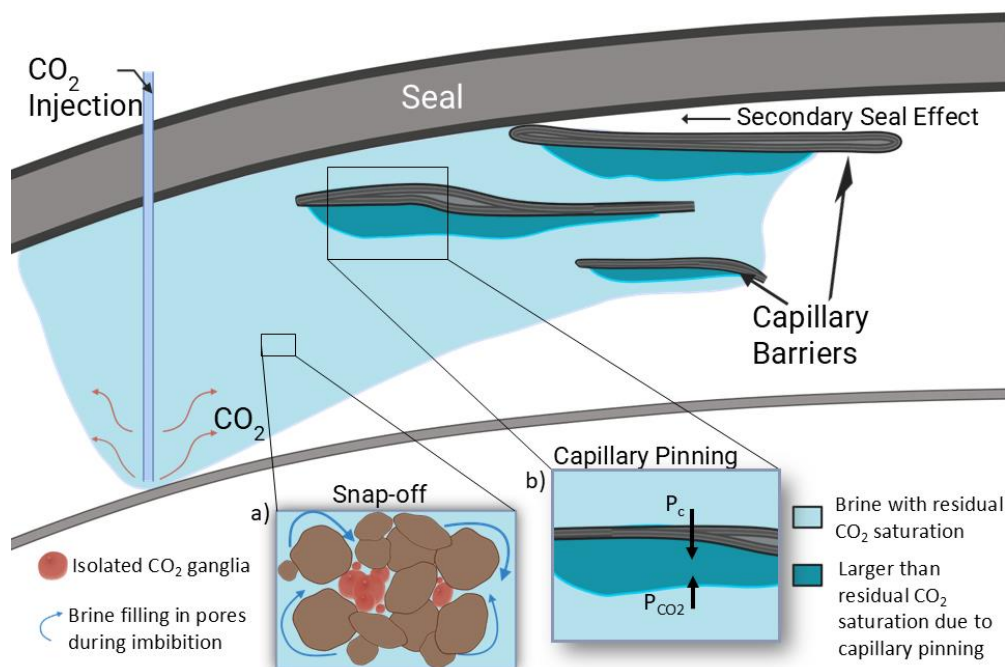


Figure 1 Schematic illustration of the two capillary trapping mechanisms of CO₂ in the subsurface (a) snap-off and (b) capillary pinning (modified after Gershenzon et al., 2017; Juanes et al., 2006). Capillary pinning leads to a higher trapped CO₂ saturation than that achievable by snap-off alone (i.e., > residual saturation). The color-coded regions represent CO₂ saturation, but the sizes and shapes of the darker blue plumes are not to scale.

Methods

To investigate how capillary pinning interacts with reservoir architecture, we conducted multiphase flow simulations using surface-based models informed by high-resolution outcrop analogue data from a wave-dominated shoreface sandstone parasequence (Figure 2). These models explicitly incorporate sedimentological heterogeneities, including clinoform geometries, facies juxtapositions, and early diagenetic cementation (Jackson et al., 2009; Sech et al., 2009), all of which condition spatial variations in both permeability and capillary entry pressure.

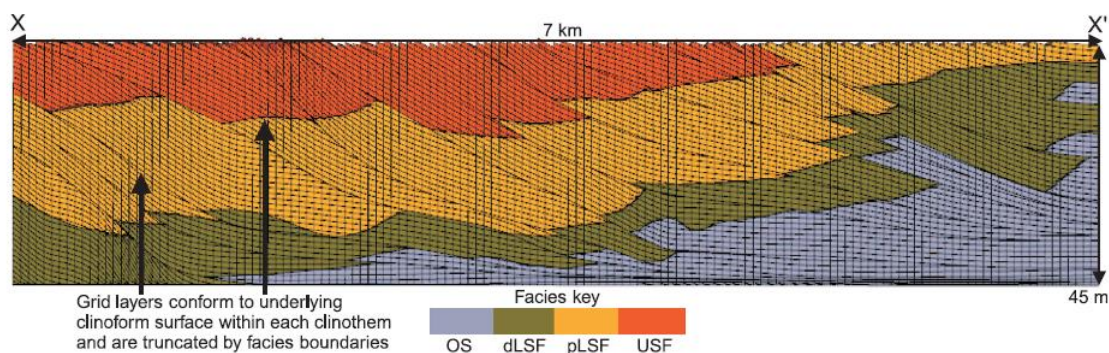


Figure 2 Two-dimensional section of the facies model illustrating the cornerpoint grid designed to represent the complex facies architecture controlled by clinoforms in a wave-dominated shoreface sandstone parasequence (Sech et al., 2009). Grid layers are nominally 1 meter thick; dLSF = distal lower shoreface and inner shelf; pLSF = proximal lower shoreface; OS = offshore shelf; USF = upper shoreface.

Our results show that these features impose significant capillary barriers that laterally spread and locally immobilize the CO₂ plume. This lateral spreading leads to more extensive residual trapping while delaying vertical migration. These capillary barriers also contribute to flow compartmentalization and hinder pressure dissipation, reducing injectivity and enhancing transport anisotropy. When these traps are assumed to persist indefinitely, they represent an upper bound on long-term CO₂ storage capacity.

Comparison with waterflood simulations highlights the distinctive behaviour of CO₂-brine systems. Unlike water-oil systems, which tend to advance more uniformly and are relatively insensitive to fine-scale capillary heterogeneity, CO₂-brine systems exhibit pronounced sensitivity due to a combination of gravitational and viscous instabilities. The main driver for this difference is not in the magnitude of capillary entry pressure itself, but the fact that capillary pressure effects strongly amplify gravitational instabilities in CO₂-brine systems. These instabilities are more pronounced because of the larger density contrast between CO₂ and brine compared to that of oil and water. In addition, CO₂-brine systems are often viscously unstable, with less viscous CO₂ displacing more viscous brine, whereas waterflooding of oil is generally viscously stable. This interplay between capillary, gravitational, and viscous forces leads to complex, fingered plume morphologies and non-uniform migration paths in CO₂ storage scenarios.

Conclusions

Based on this understanding, we identify several critical research directions: (1) incorporating anisotropic capillary heterogeneity and flow directionality into upscaled models; (2) developing reservoir-scale simulation methods that resolve fine-scale dynamic capillary effects; (3) revisiting injectivity and capacity estimates in light of capillary pinning; and (4) using capillary pinning as a

diagnostic lens to better evaluate other time-dependent CCS mechanisms. In addition, we demonstrate that reusing petroleum reservoir simulation approaches for CCS may require significant modification to account for the fundamentally different fluid properties, flow instabilities, and capillary phenomena that dominate CO₂-brine systems.

Ultimately, this integrated approach, merging literature review and geologically realistic simulation, advances a more realistic and rigorous framework for CO₂ storage assessment. By explicitly incorporating capillary pinning and its associated instabilities into modeling workflows, we can more accurately predict storage behaviour, optimize injection strategies, and enhance the long-term security of CO₂ sequestration in stratigraphically complex reservoirs like those in the North Sea.

Acknowledgements

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