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Foundation concepts for geological carbon storage modelling and the Atlantic Canada context

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Summary

Geological Carbon Storage (GCS) is a key component of Canada's energy transition, enabling the long-term sequestration of carbon dioxide (CO_2) in deep subsurface formations. Offshore Atlantic Canada represents a promising frontier for GCS development due to favourable basin architecture, extensive seismic and well datasets, and legacy offshore infrastructure from hydrocarbon exploration and production. Major sedimentary basins, including the Scotian Basin, Jeanne d'Arc Basin, and Orphan Basin, contain thick saline aquifers, structural and stratigraphic traps, and regionally effective caprock seals that are critical for secure CO_2 storage.

Effective GCS deployment depends on robust, fit-for-purpose geological modelling workflows that integrate structural and stratigraphic frameworks with reservoir properties, pressure regimes, and containment risk. The foundational elements of geological carbon storage modelling include structural, stratigraphic, geometric, and topological frameworks, coupled with numerical reservoir simulators to evaluate CO_2 plume migration, pressure evolution, and storage performance. These workflows support key project decisions across the GCS lifecycle, from regional screening and site selection to injection design, monitoring, and post-closure assessment, using metrics such as capacity, injectivity, containment, and storage efficiency.

Experience from international offshore GCS projects, including Sleipner, Snøhvit, Northern Lights, Tomakomai, and Porthos, provides practical lessons in infrastructure reuse, monitoring and verification design, and regulatory evolution. These examples underscore the value of hub-based development models and early demonstration projects in de-risking storage and building stakeholder confidence. Key challenges for offshore Atlantic Canada include complex structural geology, localized overpressure, and salt tectonics, highlighting the need for high-resolution geological models and probabilistic assessment approaches. Recommended next steps include integrated basin-scale modelling, uncertainty-based capacity evaluation, and development of a regional offshore carbon storage atlas. As regulatory frameworks mature, offshore Atlantic Canada is well positioned to play a leading role in Canada's large-scale geological CO_2 storage portfolio.

Geological Setting and Storage Potential

The offshore Atlantic Canada margin formed during the breakup of Pangea and exhibits a rift–drift–sag tectonic evolution that strongly influenced basin architecture, sedimentation, and trap development. Rifting during the Jurassic to Early Cretaceous created fault-bounded sub-basins, followed by thermal subsidence and deposition of thick post-rift sedimentary sequences. This evolution produced multiple reservoir–seal pairs suitable for GCS.

The Scotian Basin offshore Nova Scotia contains thick Mesozoic–Cenozoic clastic successions, including regionally extensive saline aquifers within the Missisauga and Logan Canyon formations, sealed by marine shales and carbonate units. Offshore Newfoundland and Labrador,

the Jeanne d'Arc and Orphan basins host productive hydrocarbon reservoirs such as the Ben Nevis, Hibernia, and Jeanne d'Arc formations, as well as deeper saline aquifers with significant storage potential.

Previous regional assessments suggest that offshore Atlantic Canada could accommodate very large volumes of CO_2, potentially at the gigatonne scale. However, capacity estimates are sensitive to geological complexity, pressure regimes, reservoir connectivity, and uncertainty in petrophysical properties. Overpressure zones, fault compartmentalization, and salt tectonics—particularly in parts of the Scotian and Jeanne d'Arc basins—require careful evaluation through detailed geological and numerical modelling.

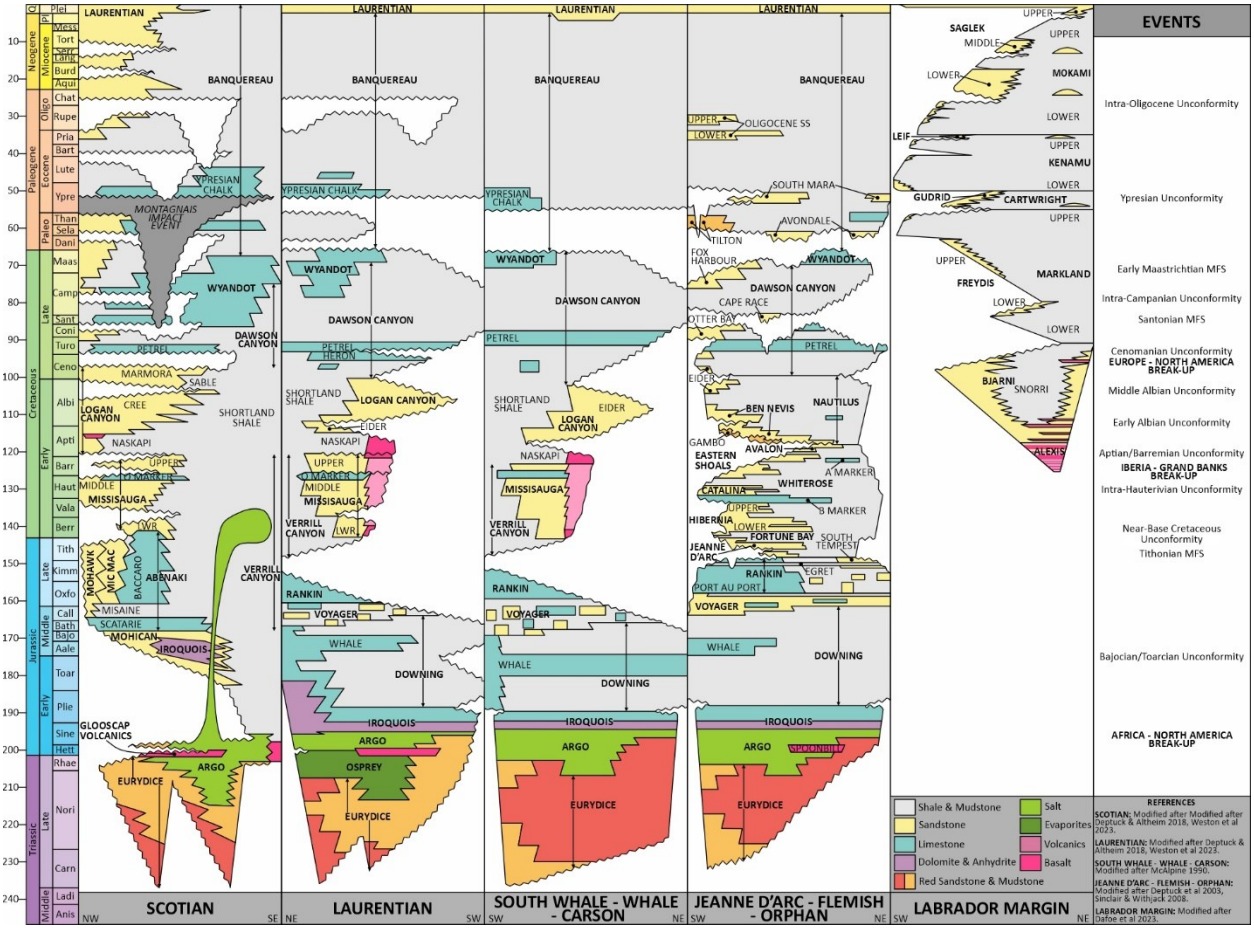


Figure 1: Lithostratigraphic columns for the Scotian, Laurentian, South Whale, Whale, Carson, Jeanne d'Arc, Flemish Pass, Orphan, and Labrador Margin basins. Modified after Deptuck et al. (2003), Sinclair and Withjack (2008), Deptuck and Altheim (2018), Dafoe et al. (2023), and Weston et al. (2023).

GCS Modelling Frameworks & Methods

Robust geological modelling is fundamental to GCS development, particularly in structurally complex offshore settings. Geological carbon storage models typically integrate four interrelated frameworks: structural, stratigraphic, geometric, and topological.

The structural framework defines faults, folds, and salt bodies that control reservoir compartmentalization, trap geometry, and potential leakage pathways. Accurate fault interpretation is essential for assessing pressure communication, plume migration, and containment risk.

The stratigraphic framework establishes vertical and lateral relationships between formations, ensuring consistency in depositional sequences, reservoir continuity, and seal distribution. Sequence stratigraphic frameworks developed for hydrocarbon exploration provide a strong foundation for GCS assessments in Atlantic Canada.

The geometric framework translates geological interpretations into three-dimensional surfaces and volumes used for grid construction. Correct representation of reservoir thickness, structural closure, and lateral extent is critical for capacity estimation and simulation accuracy.

The topological framework ensures that geological units and fault blocks are correctly connected within the model. In complex settings, small topological inconsistencies can significantly alter predicted fluid flow pathways and storage performance.

These frameworks form the basis for static geological models and dynamic numerical simulations. Numerical modelling evaluates multiphase flow of supercritical CO_2 and brine, pressure evolution, and trapping behaviour over time. Early-stage models are typically basin-scale and focus on screening and capacity estimation, while later-stage models become more detailed and site-specific, incorporating calibrated petrophysical properties and refined boundary conditions.

International Analogues

International offshore GCS projects provide valuable analogues for Atlantic Canada. Long-running operations such as Sleipner and Snøhvit demonstrate the feasibility of large-scale offshore CO_2 storage and the importance of continuous monitoring and model validation. Time-lapse seismic monitoring at these sites has been instrumental in tracking plume migration and verifying containment.

Newer developments, including Northern Lights, illustrate the effectiveness of hub-based storage models that allow multiple emitters to share transport and injection infrastructure. This approach is particularly relevant for Atlantic Canada, where industrial CO_2 sources are geographically dispersed.

Demonstration and planned projects such as Tomakomai and Porthos highlight the value of early pilot projects, robust monitoring programs, and transparent regulatory processes. These projects underscore that public confidence is closely tied to clear communication of monitoring results and proactive risk management.

Implications for Offshore Atlantic Canada

While offshore Atlantic Canada has strong geological potential, several technical challenges must be addressed. Structural complexity, including faulted reservoirs and salt-related deformation, complicates trap analysis and plume prediction. Overpressure may limit injectivity and require careful pressure management strategies. Data density varies significantly across the region, with sparse coverage in some frontier areas.

Addressing these challenges requires targeted data acquisition, high-resolution geological modelling, and probabilistic approaches to capacity and risk assessment. Development of a regional offshore carbon storage atlas would provide an integrated framework for geological data, modelling results, and regulatory planning. Opportunities also exist to repurpose existing offshore infrastructure, including depleted fields and pipeline corridors, to reduce development costs and environmental footprint.

Conclusions

Geological carbon storage represents a significant opportunity for offshore Atlantic Canada to contribute to Canada's emissions reduction objectives. The region's favourable geology, extensive subsurface datasets, and offshore operational experience provide a strong foundation for large-scale CO_2 storage. Integrated geological modelling and numerical simulation are central to realizing this potential, supporting informed decisions on site selection, capacity estimation, and risk management.

Lessons from international offshore GCS projects demonstrate the importance of robust modelling workflows, adaptive management, and transparent monitoring. Although technical challenges remain—particularly related to geological complexity and pressure behaviour—these can be addressed through targeted modelling, pilot projects, and collaborative planning. With continued investment and coordination, offshore Atlantic Canada is well positioned to become a key contributor to safe and effective geological carbon storage.

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