The Norwegian elephant awakens: The CCS reservoir for Northern Scandinavia

Kristian B. Brandsegg[1]*, Sougata Halder[1], Allan McKay[1], Bent Kjølhamar[1] and Gunhild Myhr[1] illustrate how the repurposing of high-quality seismic data and state-of-the-art geophysical workflows can significantly lower entry barriers for CCS projects.

Abstract

The rapid scale-up of carbon capture and storage (CCS) on the Norwegian Continental Shelf requires robust, cost-effective subsurface screening, characterisation, and long-term monitoring solutions. Advances in marine seismic acquisition and processing play a central role in reducing geoscience uncertainty and accelerating storage site maturation. This article highlights recent technological achievements in CCS enablement, demonstrated by the Elephant CCS project in the Norwegian Sea, a large-scale multi-client dataset repurposed for carbon storage applications.

The Elephant project leverages modern 3D broadband seismic data processed using both pre-stack depth migration and high-fidelity velocity model building. A key innovation of the dataset used to mature the Elephant CCS site is its ability to resolve depositional architectures and stratigraphic heterogeneity relevant to horizontal permeability distribution and plume migration behaviour. Broadband processing and geomorphological interpretation provide new insights into reservoir continuity and seal effectiveness, critical for derisking site selection and informing dynamic modelling. Furthermore, the project demonstrates how multi-client seismic libraries can form a scalable foundation for future 4D seismic monitoring, establishing a baseline for time-lapse surveillance of CO_2 injection.

Together, these advances illustrate how the repurposing of high-quality seismic data and state-of-the-art geophysical workflows can significantly lower entry barriers for CCS projects. The Elephant CCS project exemplifies the utilisation of high-quality seismic data combined with analytical tools and workflows for delivering fit-for-purpose subsurface intelligence to support Norway's ambition for gigaton-scale CO_2 storage and the broader energy transition.

Introduction

Northwest Europe is a global leader in cross-border CCS developments (Global CCS Institute, 2025). Early projects have largely been national-centric, with Norway drawing on nearly 30 years of operational experience from Sleipner and Snøhvit CCS projects (Ringrose, 2020). Major initiatives also include Teesside-Humber, Acorn and HyNet (UK), Greensand (Denmark), and Aramis and Porthos (Netherlands). Large hubs are now maturing within these regions, e.g. Northern Lights in Norway are designed to store both local and long-distance transported CO_2. The increase in cost-efficient storage sites is expected to drive competitive pricing and market maturity.

Given the history of hydrocarbon exploration and production, the majority of active sedimentary basins have sufficient data that can be repurposed for subsurface evaluation for developing a CO_2 storage concept. However, to progress efficiently from initial screening to CO_2 storage site maturation, projects rely on high-quality seismic data for reservoir characterisation, injection planning and leakage monitoring. Often, legacy seismic data is generally sufficient for early-stage storage concept building; the key challenge lies in ensuring long-term reservoir integrity, optimised injection, and effective monitoring over decades. With access to modern, high-quality 3D seismic data, the evaluation process can be accelerated cost-effectively. As CCS costs currently exceed EU CO_2 prices, the cost efficiency of the CCS project, especially within 4D monitoring programs, is critical. Integration of geological, geophysical and petrophysical information from subsurface well and seismic data can provide valuable insights into storage suitability for both depleted hydrocarbon and saline reservoirs, onshore and offshore (Halder et al., 2022; Halder et al., 2024).

Subsurface evaluation for carbon storage builds on decades of oil and gas industry experience, including time-lapse seismic monitoring, but also introduces new challenges such as identifying migration-assisted storage and evaluating underexplored, data-lean areas. Advances in seismic acquisition and processing from mature basin exploration have directly enabled the growth of CCS projects through cost-effective monitoring, measurement and verification (MMV) strategies (IOGP, 2025).

Developing new CCS concepts from modern high-quality seismic data in the Norwegian Sea

The Elephant CCS project represents a frontier application of high-quality seismic data to large-scale CO_2 storage assessment in the Norwegian Sea at approximately 65°N (Figure 1). Based on an extensive (>10,000 km²) broadband GeoStreamer 3D seismic dataset, the project targets Lower to Middle Jurassic saline aquifers in a region with proven favourable reservoir properties,

[1] TGS

* Corresponding author, E-mail: Kristian.Brandsegg@tgs.com

DOI: 10.3997/1365-2397.fb2026023

limited hydrocarbon prospectivity, and sparse well control. Strategically important to the development of CCS infrastructure in northern Scandinavia, this site integrates multiple trapping mechanisms, including solubility, residual (capillary) and local structural and stratigraphic trapping, indicating gigaton-scale storage potential. Advanced seismic attribute analysis enables robust aquifer characterisation in an area with limited well data and provides critical constraints for geological and dynamic models. These results form the basis for a detailed, cost-effective monitoring, measurement, and verification (MMV) plan, supporting long-term storage integrity and regulatory confidence in developing this site further.

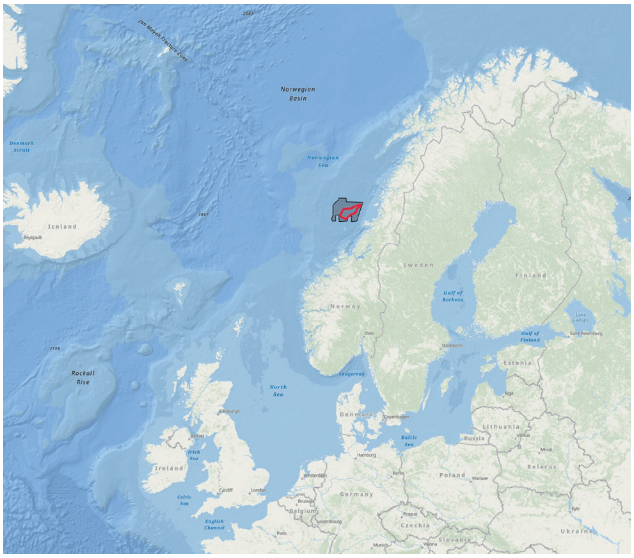

Figure 1 The mid-Norway carbon storage site is named after the seismic survey outline (grey polygon) mimicking an elephant. Red polygon indicates the main storage site.

Geological setting

The Elephant carbon storage complex is located on the Trøndelag Platform in the Norwegian Sea, adjacent to the structurally complex Halten and Dønna terraces (Bunkholt *et al*., 2021). While most available well control is derived from these hydrocarbon provinces in the west, the platform exhibits a distinct structural style, having experienced less intense deformation than the rotated fault blocks that dominate the terrace areas following Late Triassic–Jurassic multiphase extension (Figure 2). The Trøndelag Platform is separated from the terraces by the Revfallet–Bremstein–Vingleia fault complex, which became a major structural boundary during the Late Jurassic-Early Cretaceous (Figure 3). Prior to this, sedimentation across the platform and terrace regions was regionally linked, allowing depositional interpretations at the Elephant site to be informed by offset well data within a broader basin context (Martinius et al., 2011). The simplified stratigraphic column (Figure 4) outlines the regionally

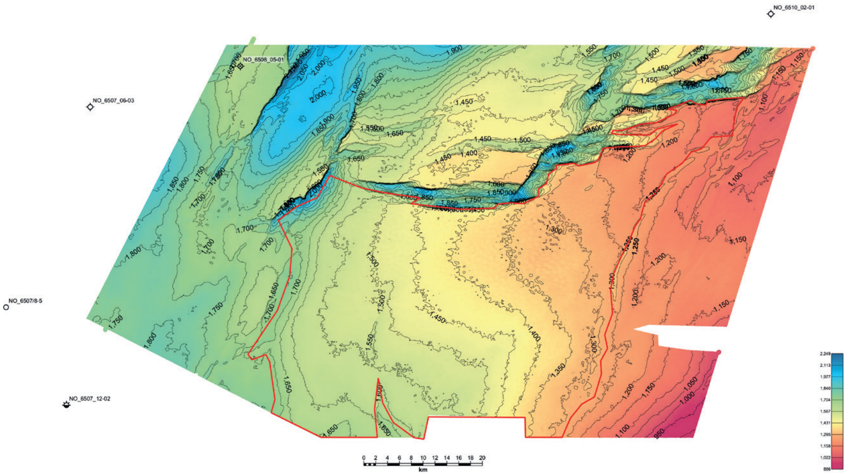

Figure 2 Wells utilised for the regional rock physics models are shown here with the two-way time (TWT) of the Base Cretaceous Unconformity (BCU) horizon. The red line is the indicative outline of the Elephant storage site.

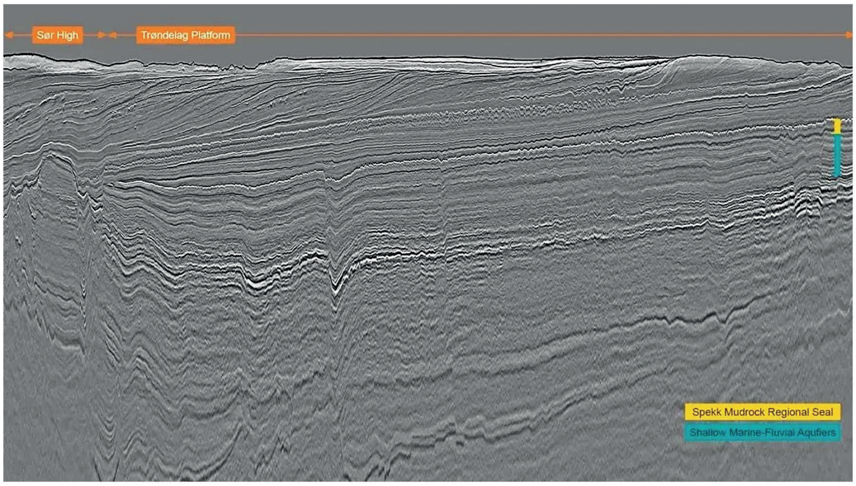

Figure 3 GeoStreamer seismic section from PGS19MO2NWS from the Sør High across the Elephant structure on the Trøndelag Platform.

extensive Upper Jurassic seals of the Melke and Spekk formations overlying multiple Lower to Upper Jurassic aquifer units that form the primary CO_2 storage intervals.

In the absence of good well control, high-quality seismic data helps to reduce uncertainties around the distribution of aquifers and seals against each other and their properties through utilising pre-stack seismic attributes, facies inversion, rock physics from offset wells and through extracting architectural elements of the sedimentary environment from seismic geomorphology.

The high quality and resolution of the 3D seismic data enable detailed mapping of the seal and overburden above the top Garn Formation, the uppermost storage unit at the Elephant site. Overburden architectures such as clinoforms, onlaps, and toe-sets are clearly imaged, allowing assessment of potential integrity risks and CO_2 migration pathways in the underlying Ile Formation aquifer (Figure 5). Faults are well resolved and can be confidently mapped to evaluate their impact on seal and overburden integrity. Seismic imaging expressed by spectral decomposition of the top Ile Formation also reveals strandplain geometries within the underlying Ile Formation, supported by reliable ties to cored offset wells (Figure 6).

Following the definition of the regional storage framework, detailed mapping of the Top Garn/Base Melke horizon highlights subtle rugose structuration that would not be resolved with lower-quality data, underscoring the value of broadband seismic data early in site evaluation. On the tectonically quiescent Trøndelag Platform, the extensional fault-derived syn-rift Garn Formation comprises laterally extensive fluvial to shallow-marine sandstones. This extensive continuity supports a migration-assisted storage concept at scale, informed by well-based analogues from the Halten Terrace expressed by the horizon-based flow modelling (Figure 5).

Consistent 3D static model

The 3D seismic data enables clear discrimination between the shale-dominated Melke and Not Formations and the sand-prone Garn Formation. Conventional horizon-based interpretation proved challenging for the Garn Formation due to pronounced lateral variations in sand content, prompting the application of a probabilistic facies inversion to more robustly delineate highsand aquifer elements. The facies inversion highlights significant lateral heterogeneity within the Garn Formation, in contrast to the more laterally continuous sandstone character observed in the underlying Ile Formation (Figure 7). Integration of seismic attributes with offset well data and rock physics-based calibration allows a data-driven characterisation of depositional elements and reservoir properties, offsetting the limited local well control. The resulting facies probability volumes provide a consistent framework for defining aquifer distribution and connectivity within the 3D static model (Figure 8).

These results fundamentally improved the conceptual understanding of reservoir architecture at the Elephant site. Isopach mapping of the Garn Formation, constrained by seismic-derived impedance and facies probabilities, reveals a predominantly north-south-orientated depositional system, differing from earlier basin-scale interpretations. In contrast, the Ile Formation forms a regionally extensive, low-impedance sandstone package with clear strandplain and prograding geometries, supported by strong seismic expression and calibration from cored offset wells (Figure 9). The ability to resolve sandstone distribution and potential connectivity between the Garn and Ile formations is critical for assessing storage capacity, injectivity, and CO_2 migration pathways (Figure 10). By directly conditioning the

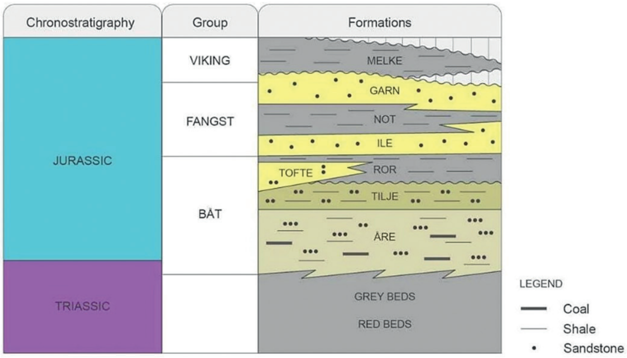

Figure 4 Simplified stratigraphy showing the distribution of aquifers and sealing lithologies based on Dalland et al. (1988).

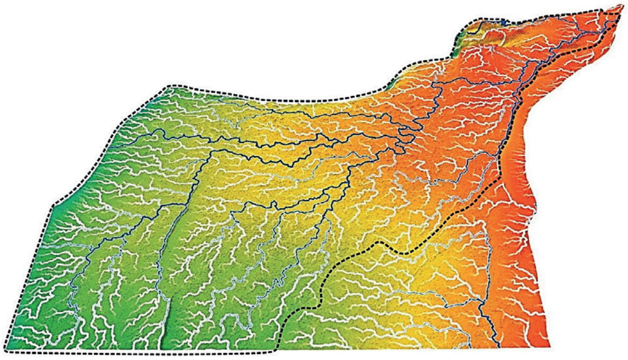

Figure 5 Using the top aquifer (Top Ile Formation) interpretation, we can use horizon-based flow modelling to determine the likely open aquifer 'fairway' to outline areas for further investigation. The dotted line is the indicative outline of the Elephant storage site.

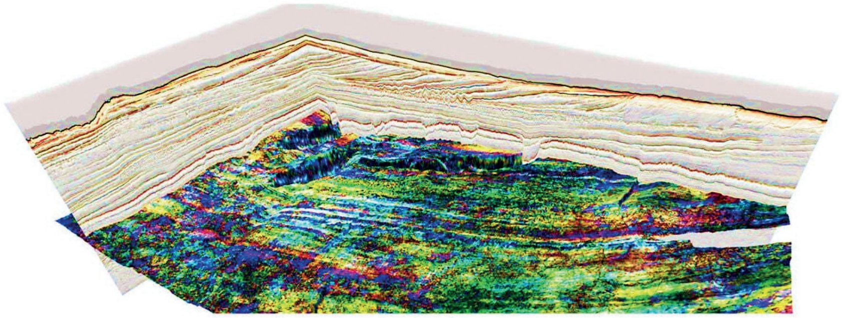

Figure 6 Chair diagram showing a combined spectral decomposition display from the Ile Formation aquifer, highlighting the spectacular strand plain geomorphology that can be extracted from the Elephant seismic dataset. Understanding depositional fabrics enables informed decisions on the orientation of horizontal permeability distributions, among other parameters, which are vital for understanding CO_2 behaviour in the subsurface.

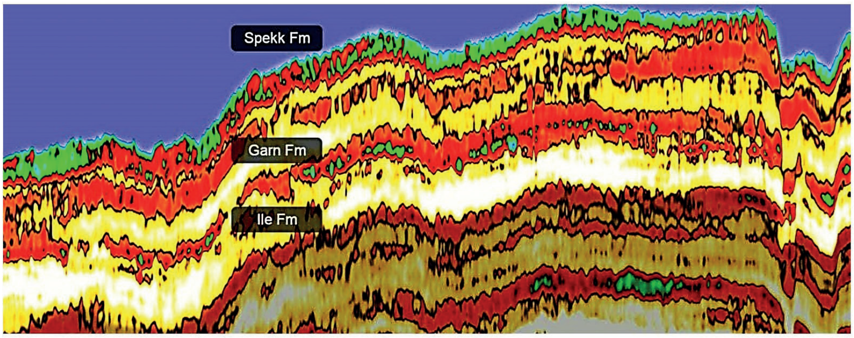

Figure 7 Seismic facies inversion showing the probability of sandstones (white/red is high probability, blue/green is low probability), highlighting the distribution of the Garn and Ile formations.

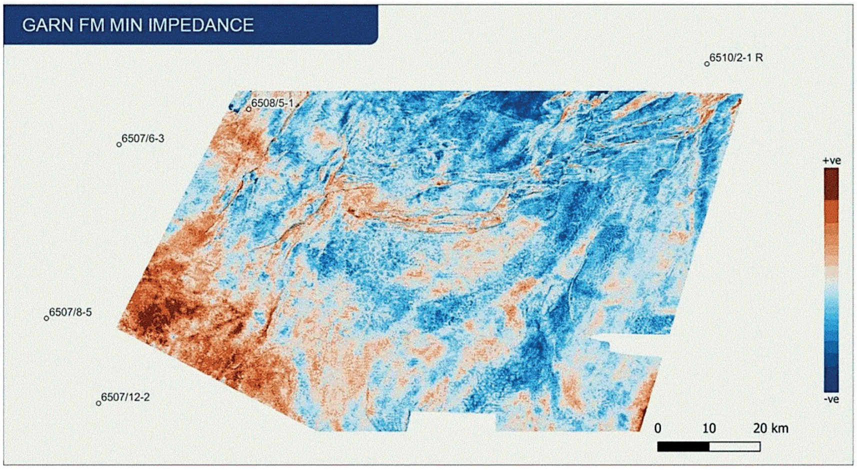

Figure 8 This Garn Formation impedance map from the high-quality GeoStreamer data guides the development of facies maps across the area of interest and highlights key geological features in the depositional element map of the aquifers that can be directly used in later steps, including reservoir modelling.

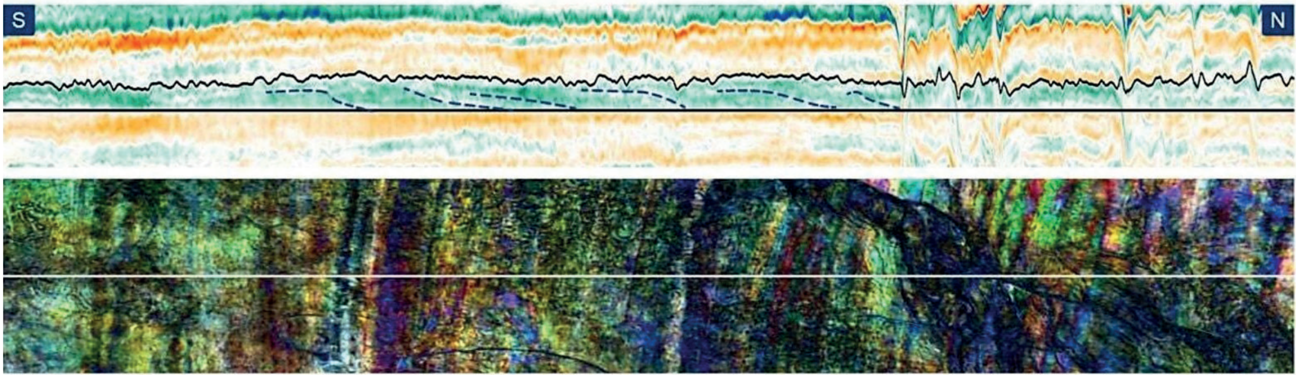

Figure 9 Prograding strand plain deposits showing across the Ile Formation in section flattened at the base and in plan view defined by spectral decomposition above.

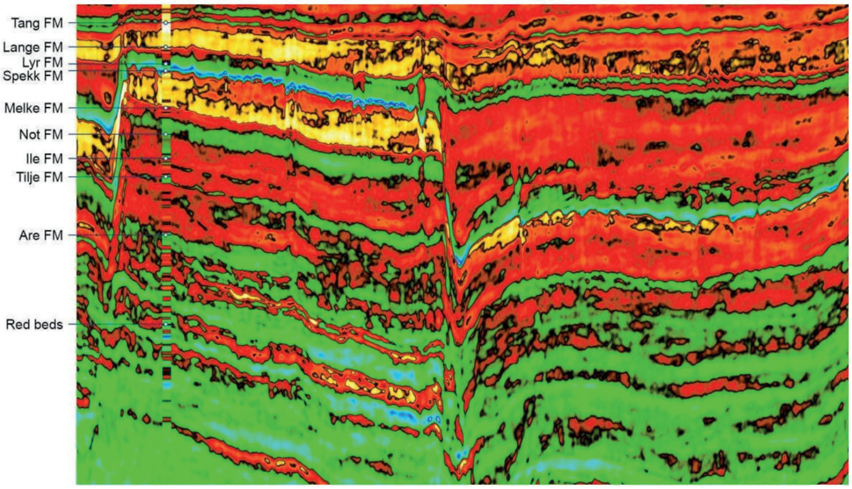

Figure 10 Total porosity transformation (filtered total porosity (PhiT) displayed on the well track – green/blue – low PhiT, orange/red – high PhiT). Notice the impressive match between the well porosity log in well 6508/5-1 and the porosity volume.

Type	KH/mD	Swi	maxKrg	Sgt
Shale/Null	0.001	0.637	3.019	0.224
Silty	3.000	0.235	2.201	0.333
Mod Sand	700.000	0.062	1.446	0.362
Good Sand	1800.000	0.049	1.344	0.363

Table 1 Reservoir parameters used in the static model construction related to the seismic facies observations in the Upper Jurassic sequence and anchored to nearby wells (KH – Horizontal permeability, Swi – initial water saturation, maxKrg – maximum relative permeability of gas, Sgt – Specific total gravity).

3D static model with seismic-derived facies and architecture, the workflow reduces uncertainty in aquifer extent and connectivity, providing a robust foundation for subsequent dynamic simulation and storage performance assessment.

Dynamic 3D model

Building on the 3D seismic-driven static model and interpreted connectivity between the Garn and Ile formations (Figures 11 and 12), a full-field 3D dynamic reservoir model was constructed to evaluate the Elephant site as a migration-assisted CO_2 storage system. The simulation model comprises ~2 million active cells (number of cells = 252 x 118 x 88; cell dimensions $\Delta X = \Delta Y = 250$ m; average $\Delta Z \approx 7.1$ m) and represents a storage complex of ~5,000 km² areal extent and ~750 m thickness. Static grids and properties (Table 1) were generated from the seismic-conditioned geological model (Figure 13), while dynamic simulations employed a black-oil formulation to represent CO_2–brine displacement, assuming pure CO_2 (<4% impurities) and modest salinity (~50,000 ppm). Reference conditions include a depth of ~1300 m true vertical depth subsea (TVDSS), initial pressure of ~2030 psi, temperature of ~57 °C, and a geothermal gradient of ~30 °C/km, with active diffusion in both liquid and vapour phases. As a stress test, injection scenarios with five wells operating at 10 Mt/yr for five years were simulated to assess plume migration, pressure evolution, and trapping efficiency. Results indicate that CO_2 migrates up-structure with dissolution, residual trapping, and local closures contributing to containment, while pressure increase remains modest even at gigaton-scale injection. Vertical migration from the Ile Formation into the overlying Garn Formation is limited, and any CO_2 reaching

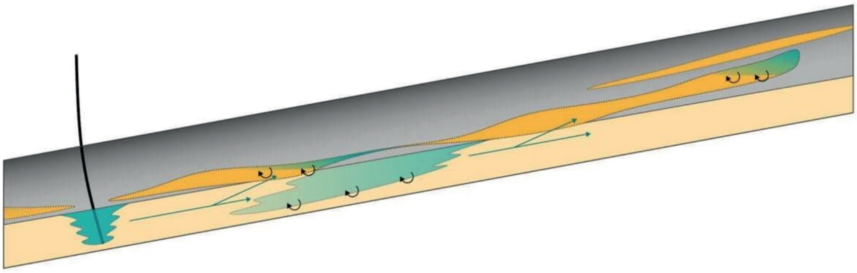

Figure 11 Conceptual sketch illustrating the potential injection strategy, where CO_2 is injected into the underlying Ile Formation and allowed to migrate up-dip, where some of it will potentially migrate into the overlying Garn Formation, the shallowest accessible sandstones within the Jurassic aquifer sequence. After injection has ceased and pressure-drive have stopped, the CO_2 is likely to move due to buoyancy.

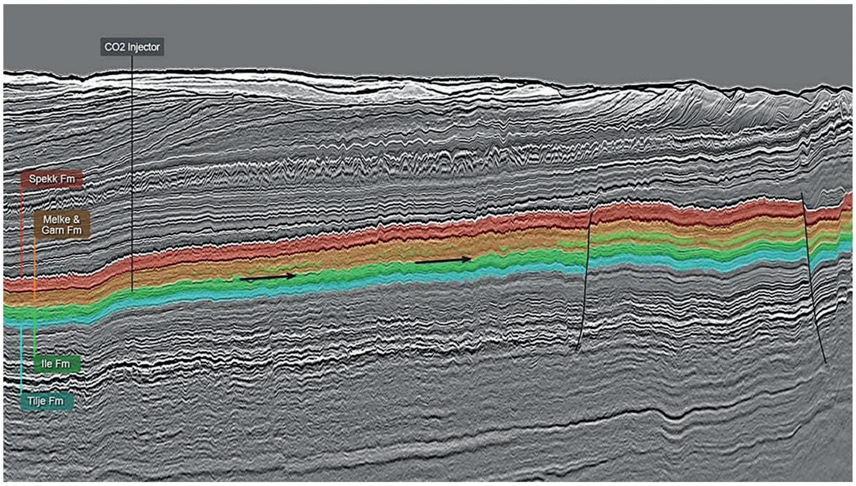

Figure 12 Regional schematic section through the proposed Elephant open aquifer storage site illustrating the prospective aquifer packages and the overlying shaly Spekk Formation regional seal for carbon storage within Jurassic sandstones. The notion is to inject CO_2 down dip and allow migration to allow CO_2 to trap residually and in dissolution.

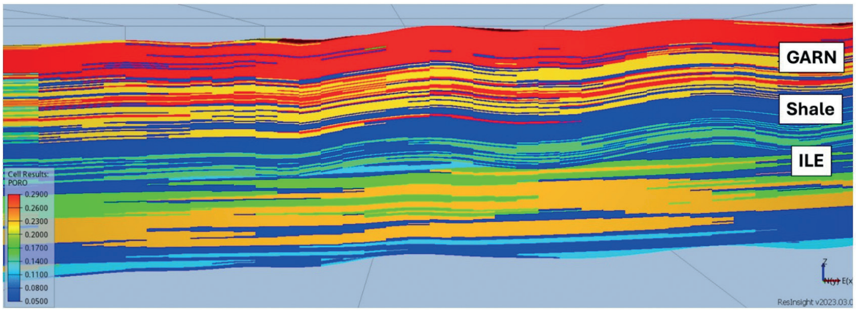

Figure 13 Lateral extent of the Upper Jurassic sequence expressed by porosity.

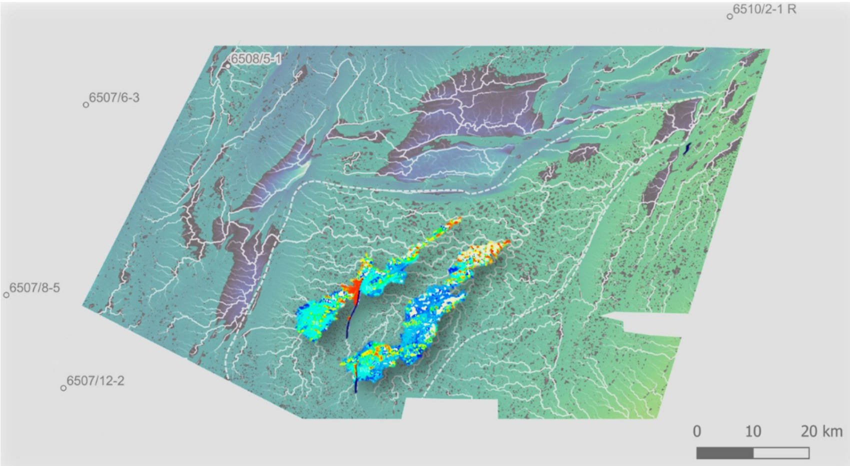

Figure 14 The initial dynamic modelling results (total 250 Mt injection from 5 injector wells over 5 years) show that the Elephant CO_2 storage prospect should not see dangerous pressure increase from the injection of 1 Gt. The CO_2 injected in the Ile Fm. appears to have little prospect of flowing upward into the overlying Garn Fm. Whatever CO_2 does reach the Garn Formation would appear to stop migrating around 2000 years after injection. The risk of CO_2 migrating from the Elephant aquifer site appears very low.

the Garn Formation is predicted to become immobilised within approximately 2000 years post-injection, suggesting a low risk of long-term CO_2 migration beyond the defined storage complex (Figure 14).

Monitoring, Measurement and Verification (MMV) plan considerations

A crucial part of the development plan for a CO_2 storage site is the formulation of the MMV plan (Brandsegg et al., 2026). The MMV plan needs to be both indicative and evolutionary whilst remaining cost-effective in operation, i.e., needs to show the most likely approach based on current knowledge and technology status, but be flexible and adaptable as the site's operations progress. A risk-based approach is recommended (IOGP 2022) whilst ensuring the regulatory and societal requirements are met to enable verification of containment of the CO_2 and conformance of the storage site to expected behaviour. Precise geological characterisation for defining CO_2 plume movement and risk assessment for CO_2 leakage is critical for developing MMV plans for carbon storage projects. Here, we consider one core element of the MMV plan for the Elephant site: subsurface time-lapse monitoring using seismic data. As outlined previously, accurate subsurface modelling based on a robust baseline 3D seismic survey prior to the beginning of the injection operation is critical for assessing and maintaining the long-term storage site integrity.

Key mechanisms for the Elephant site are migration-assisted storage and reliance on multiple trapping mechanisms that are both complicated and have differing lengths and timescales. In addition, whilst the risk of leakage from legacy wells is close to zero, the consequent lack of well control – and associated knowledge gained from hydrocarbon production – means that some subsurface elements are under constrained, e.g., depth control of the gently sloping aquifer and connectivity of key units such as the Ile and Garn formations. Being able to monitor the spatio-temporal evolution of the CO_2 plume in a cost-effective fashion is crucial and forms part of the core MMV plan, e.g., to verify containment of the injected CO_2 in the storage unit and derive estimates of plume migration speed (e.g., Acuna *et al.*, 2024) as a key indicator of conformance with dynamic model predictions.

Klüver and Day (2025) outlined an integrated seismic survey design approach that exploits a well-sampled 3D baseline survey to optimise the geometric repeatability – a key criterion in seismic time-lapse monitoring – of differing seismic methods to enable an evolutionary approach to mapping the CO_2 plume extent in 3D. In addition, David et al. (2024) outlined that hybrid surveys comprising short streamers and sparse self-recovering Ocean Bottom Nodes could be used together with advanced imaging such as Full Waveform Inversion (FWI) to provide a cost-effective and operationally flexible approach to seismic monitoring. It would appear to be feasible to employ these kinds of survey design, acquisition and imaging approaches to optimise the core MMV plan for the Elephant site, with initial monitoring efforts being focused on injection wells and larger-scale surveys reserved for future monitoring efforts as the plume extent grows. In addition, the core MMV approach should be complemented with early warning systems and/or triggers, with suitable contingency planning. Being able to capture and interrogate data from multiple sources (e.g., injection wells in near real time), integrate new technologies (e.g., Hunnestad et al., 2026) and assimilate into models of storage site performance will be crucial.

The Elephant carbon storage site is a vital part of CO2 logistics in Mid- and Northern Norway

SINTEF led a recent study on CO_2 logistics in Northern Norway, completed in January 2026, and this study includes the techno-economic analysis for the region (Skagestad et al. 2026). It demonstrates that long transport distances, dispersed emission sources, and limited existing pipeline infrastructure favour ship-based CO_2 transport combined with coastal hub solutions as the most robust and scalable early phase CCS pathway for the region. The study highlighted a hub-and-spoke logistics concept, with liquefaction, intermediate storage, and ship transport enabling phased capacity build-up and reduced upfront investment risk, while remaining compatible with future pipeline development as volumes increase. Within the evaluated logistics scenarios considered in the study, the Elephant carbon storage site was identified as a particularly attractive candidate with its extensive seismic coverage, large capacity, and flexible injection concepts. Its location, scale, and compatibility with both direct offshore injection and shore-based terminal solutions align well with the recommended logistics framework. The Elephant storage site is a preferred storage destination for Northern Norway CCS value chains as they mature and integrate into a Northern Scandinavia CO_2 transport and storage network.

Conclusion

Early integration of regional subsurface evaluations into CCS projects allows operators to align regulatory, commercial, and operational priorities while safeguarding both storage integrity and compliance with the predicted model. High-quality seismic coverage of the entire storage complex is essential for accurate subsurface characterisation and modelling for early derisking injection operation and storage containment. The key aspects for Elephant carbon storage site are:

Elephant site positioning: The Elephant carbon storage site in Mid-Norway is strategically located and supported by extensive regional 3D seismic data, providing the subsurface confidence required for large-scale storage while remaining adaptable to evolving CCS infrastructure concepts.

Strategic site selection: Effective CO_2 storage site selection must avoid conflicts with existing and future oil and gas developments, preserving hydrocarbon value, infrastructure integrity, and long-term field management while enabling early alignment of CCS with regional subsurface planning.

Infrastructure flexibility: The site offers multiple development pathways, including integration with fixed onshore facilities (e.g. pipeline to the Kråkøya terminal) and floating direct-injection solutions, ensuring future-proof deployment without constraining transport or injection strategies from Northern Scandinavia and beyond.

Integrated MMV framework: A cost-effective and robust MMV strategy is best achieved through a complementary suite of geophysical technologies, including ultra-high resolution 3D seismic, advanced streamer acquisition, ocean bottom nodes, and DAS/VSP, supporting long-term storage assurance and the successful development of the Elephant carbon storage site.

Coexistence with other marine uses: As offshore wind and other marine activities increasingly overlap with CCS prospects, high-quality seismic coverage is essential to ensure safe spatial planning, accurate subsurface characterisation, and long-term operational compatibility.

Acknowledgement

TGS is thanked for permitting the sharing of work conducted on the Elephant carbon storage site using PGS19MO2NWS seismic data. Appreciation is also extended to Bill Powell for his valuable expertise and contributions.

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