Seismic-led exploration and characterisation of carbon storage sites

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discuss the value of recent technological advances in seismic acquisition and processing for CCS site-screening projects, using multiple case studies from offshore north-west Europe.

Introduction

In many ways, subsurface projects for offshore carbon storage follow the same principles and geophysical methods that have been employed for decades in the oil and gas industry (O&G). One example of this is the adoption of seismic time-lapse technology to monitor changes in fluid saturation and migration in the subsurface, a technology that has been adopted in both oil field reservoir management and carbon storage monitoring. However, the search for more suitable storage sites does present new challenges and opportunities to the subsurface community, whether that be searching for sites that consider different storage and trapping mechanisms without the need for discrete trap geometries (so-called migration assisted storage) or re-examining areas with no expected access to petroleum charge in underexplored, data-lean areas.

In recent years, north-west Europe there has been more co-located petroleum and CCS (carbon capture and storage) activities, with increased near-field O&G exploration co-existing alongside CCS site evaluation. Northern Lights is probably the best-known example of this, with its close geographical association with the giant Troll field (Furre et al., 2019). The increasing pressure to develop oil and gas reserves has resulted in significant advancements in seismic acquisition and processing technology. This progress has been particularly instrumental in supporting exploration efforts in mature basins, where enhancing the quality of seismic information has been crucial. These advances have spurred the emergence of a growing number of CCS projects.

Using seismic information for site selection

3D seismic data plays a critical role in both the understanding and mapping of the subsurface geology as well as quantifying properties that are relevant to CO2 storage, such as injectivity, trap mechanisms, and fluid migration. Whilst the source rock identification and hydrocarbon migration history may not be as relevant for CCS, many aspects other than trap mechanisms require a far more extensive basin-scale and reservoir-scale understanding such as derisking seals and the complete characterisation of the overburden. Screening for CCS sites using seismic data benefits from large amounts of spatial 3D data points, especially when considering saline aquifers, and from appropriate illumination from the seabed down to the lowest potential injection point, but not as deep as is typical for hydrocarbon source rocks. Fortunately, in the mature Europe basins a large amount of seismic data is available for repurposing.

The seismic industry has already demonstrated that rejuvenating legacy datasets can provide valuable insight for early storage concept studies. Processing technologies have come a long way in reducing the differences in the end results due to different acquisition systems and configurations. However, further developing a CCS site may require more information than is adequate for screening purposes. Still, in some cases, new data acquisition may be required either for more accurate quantification of capacity, further derisking of seals, or for establishing a new reference for storage models and subsequent requirements for monitoring. We review three different case studies from the UK Southern North Sea, the Norwegian North Sea, and the Norwegian Sea, in which data were (re)processed with modern imaging technology. We will highlight the value of the new datasets by focusing on various CCS storage concepts, based on saline aquifer models, but also identify possible areas for improvements as well as mitigating factors and processes.

Reprocessing legacy data at a regional scale for efficient CCS screening

The Southern North Sea (SNS) has a long history of petroleum exploration with production starting in the 1960s (Cameron et al. 1993), and with recent exploration successes it has been identified as a key area to achieve net zero objectives. The SNS Vision project, initiated by PGS in late 2022, exemplifies how the seismic imaging quality from rejuvenated multi-survey vintage data, can be enhanced to provide new products fit for both O&G exploration and CCS screening.

The common final Kirchhoff pre-stack depth migrated (KPSDM) products cover 26 legacy seismic surveys acquired between 1988 and 2006. It consists of approximately 12,000 km^2 of 3D seismic data predominantly located in the UK sector and with parts in the Dutch sector, and provides a regionally consistent dataset for both structural, stratigraphic and quantitative interpretation purposes. Both pre- and post-salt intervals, whose depths vary greatly, were the main objectives of the reprocessing,

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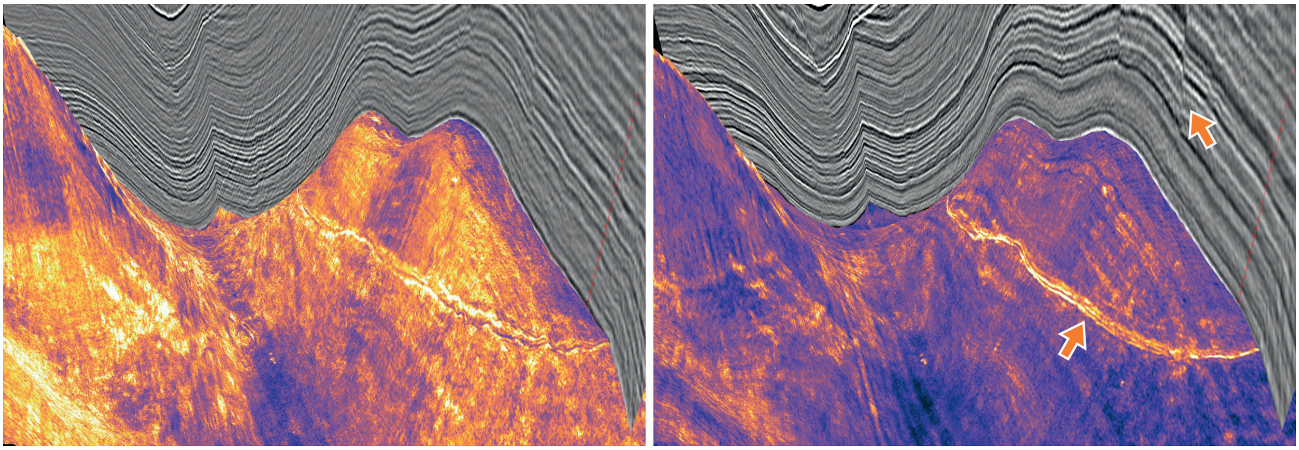

Figure 1 Incoherence attribute extraction at the top of the Bunter sandstone horizon, from the legacy KPSTM full stack (left) versus the reprocessing results (right) over the Endurance area. The strong incoherence response (orange to white) on the legacy KPSTM is not necessarily consistent with geological events and adds uncertainty to the interpretation of faults and fractures. The phase reversal is better outlined on the latest SNS dataset, as well as the fault system towards the north (arrows).

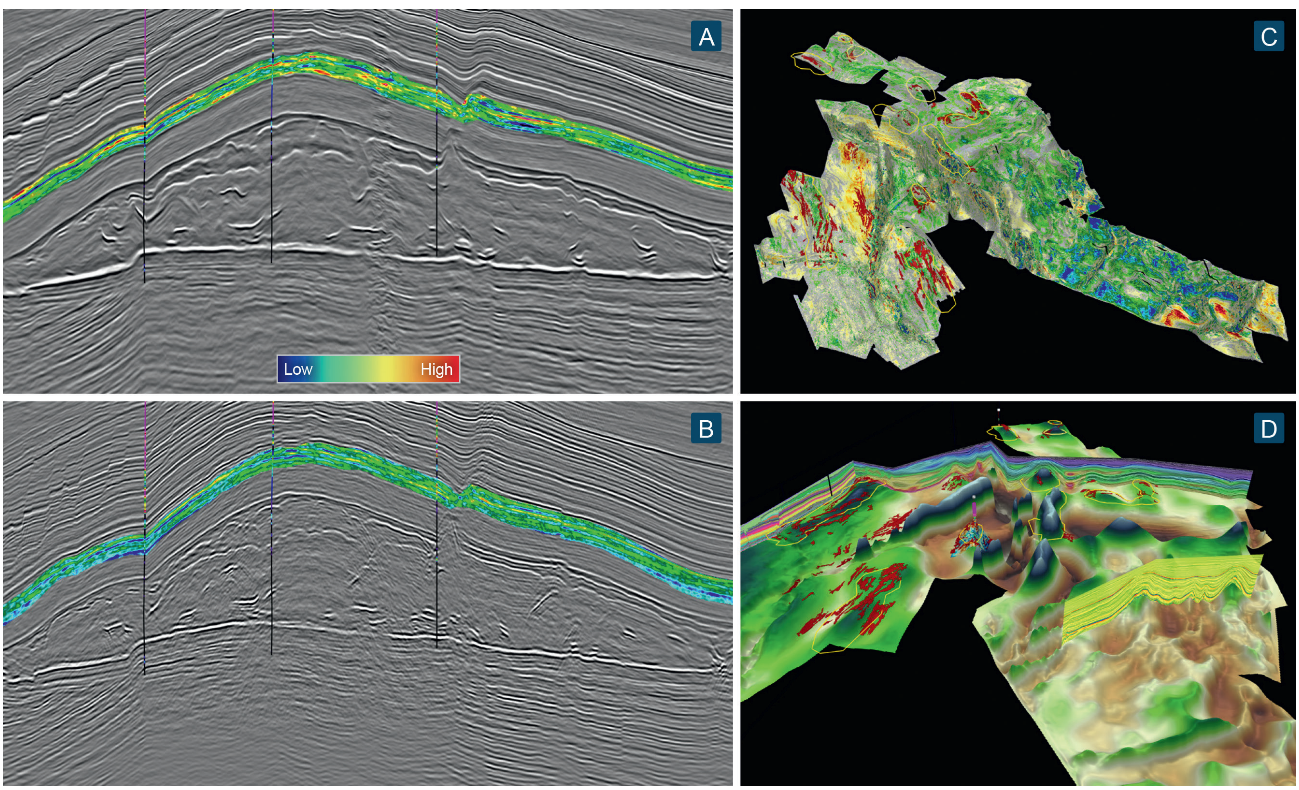

Figure 2 On the left: porosity prediction rendered in a 300-m interval from Top Bunter, co-rendered with the reprocessed final KPSDM stack (a) and legacy KPSTM stack (b) showing significant changes in the distribution and variation across the sand units and structures. The porosity is extracted over the same interval and rendered in 3D over the full 12,000 km^2 reprocessed area (c) with an outline of structures of interest, which are represented in a 3D model (d).

including an extensive velocity model building (VMB) sequence. The reprocessing, on a common grid of 12.5 m x 12.5 m and 2 ms temporal sampling, also addressed several challenges due to the different acquisition systems and geometries, which were amplified by the very shallow water depth (approximately 12-95 m) and the complex geology, all reviewed in detail by Rumyantsev et al. (2023).

Quality improvements were significant at all depths, notably in the modeling and imaging of intra-salt heterogeneities and base salt anhydrites/dolomites, as well as at the deeper pre-salt Rotliegend which is mainly a target for gas exploration. The step change is even more significant in the post-salt section where a significant focus for CCS ventures is currently put on the Triassic Bunter sandstones and the overburden. Indeed, those intervals were historically poorly focused and therefore insufficiently imaged. The latest improvements are further emphasised by greater clarity of faults, some of which extend from top salt to near surface, a component that is critical for fully assessing containment risks.

Figure 1 shows a significant change in the incoherence attribute extracted at the top of the Bunter sandstones over the Endurance area. The high incoherency response (white values) is spread across the area on the legacy data, likely caused by random noise. The higher signal-to-noise ratio (SNR) in the reprocessed dataset considerably reduces the background trend (blue values) revealing a clear outline of the Endurance closure which is associated with the phase reversal present in the area. This phase reversal is postulated to be associated with the plugging of the reservoir sand with halite (Gluyas and Bagdu, 2020) and is an important geological feature to map as this has some effect on the site capacity and the CO2 migration.

The main KPSDM results provide reliable amplitudes for quantitative interpretation, which still proves to be a challenge in this post-salt environment due to the scarcity of available well data. Fortunately, a novel approach based on machine learning (Ruiz et al., 2021) allowed the reconstruction of missing overburden well information to support the generation of reliable rock properties (Reiser et al., 2023), in particular for the Triassic Bunter Sandstone Formation BC28, as illustrated in Figure 2.

The geometries of the legacy surveys did not allow a proper imaging of the very shallow near surface (seabed and up to several hundred metres below) in the KPSDM products, due to the inherent lack of very near offset information. Accurate imaging of the overburden is essential for a complete evaluation of CCS sites. Advanced imaging techniques, such as Separated Wavefield Imaging (SWIM, Whitmore et al., 2010) have demonstrated value for exploration (Rønholt et al., 2015) and operation derisking (Oukili et al., 2019), though in the given case studies, the data were acquired using modern multi-sensor towed-streamer systems. Similar applications have been adapted and proven for shallow water ocean-bottom seismic datasets (Anderson et al., 2022), even though the technology was not originally designed for this purpose. The principle assumes a clear separation of the up- and down-going wavefield which in the case of hydrophone-only streamer systems, may be approximated by making certain assumptions of the free surface and sensor depths and/or using advanced deghosting methods. Upon generating pseudo up- and down-going wavefields, the imaging technique may be applied in the same fashion to any type of streamer data, to reconstruct shallow, virtually zero-offset, reflectivity information.

The methodology was validated on a subset of the data and the results are illustrated in Figure 3. We can observe an improved resolution compared to the Kirchhoff image and illumination is indeed greatly recovered, revealing structures and amplitude changes of critical value for a more complete derisking of the CCS concepts in this area. We postulate that some of the assumptions in the wavefield separation, such as free surface characteristics, have an impact on the recoverable bandwidth using multiple reflection signals if those characteristics are subject to high variations caused by poor weather conditions that occurred during the acquisition.

The complementary work achieved over the great SNS area, with the inclusion of the near-surface imaging feasibility work, illustrates the significant information that can be extracted from existing data for a comprehensive CCS site screening study, as well as the adaptive thinking that is required to address the challenges with both deep, overburden and near-surface interpretation. Even so, the resolution of the near-surface image provided by this novel workflow is somewhat inferior to more modern fit-for-purpose high-resolution seismic solutions (such as ultra-high resolution or site survey) and the significant age of the dataset introduces

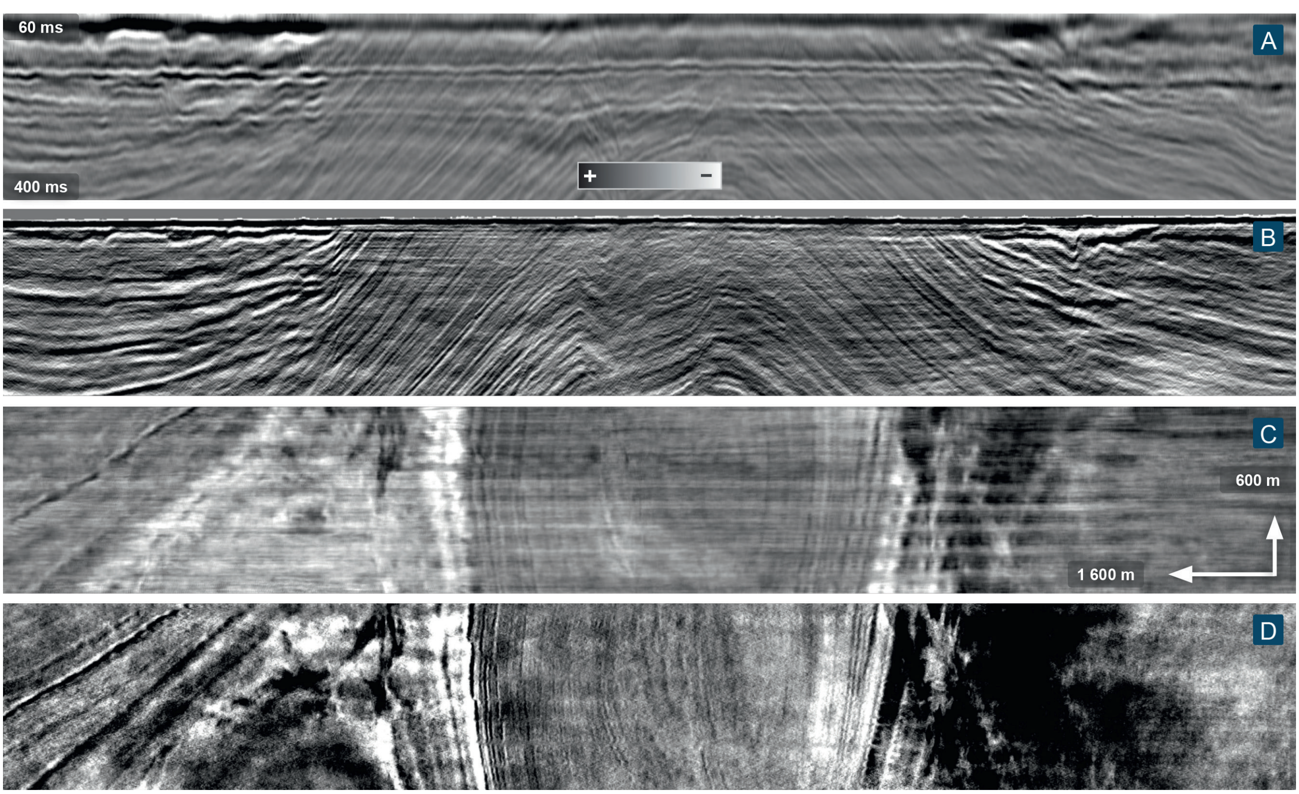

Figure 3 Cross-section and time slices (112 ms) of the KPSDM stack (a and c) and SWIM image (b and d), highlighting the complexity of the structures all the way to the seabed. The clearest sub-horizontal event in the KPSDM section (a) with the white-black-white sequence is not the seabed but a residual imprint of its first surface-related multiple reflection. This artefact has a major impact on the time slice (c). The larger folding is better outlined in the SWIM images (b, d) as well as smaller-scale folding, terminations, and possible faults within, especially on time slices.

uncertainties for accurately quantifying shallow hazards. However, it still provides critical and early insights into the containment risks, in addition to providing a more relevant basis for future work which may include new seismic acquisition and processing programs.

Focusing on new details for CCS storage definition using legacy data

In this second case study, we shift to the Norwegian sector, in the Egersund Basin, located southwest of Stavanger, which is a local deepening between the Norwegian-Danish Basin and the Stavanger Platform in the North Sea. The southern part of the basin has been more recently a high focus for CO2 storage and was included in recent CCS licensing rounds with two awards in 2023.

The Egersund Basin has a small local oil kitchen to the northwest, charging the Yme Field which is situated in the northern part of the basin. The development of lower and middle Jurassic sandstones is partly influenced by the tectonic structuring and salt movement. Later, the Upper Jurassic-Lower Cretaceous tectonic development created a series of NW-SE faults. In the late Neogene period the basin was lifted obliquely eastward and up towards the Norwegian mainland. This is a promising area with good reservoir sands, well suited for containment of substantial volumes of CO2, though with risks associated with the various tectonic episodes.

3D seismic data acquired in 2005, with a hydrophone-only streamer system, was reprocessed in 2013 focusing on gas exploration. The objectives of the recent 2023 reprocessing were to achieve high-quality subsurface imaging for shallow gas exploration purposes down to 4-5 km and CCS. Once again, the final Kirchhoff pre-stack depth imaging results, supported by a detailed velocity model principally derived using Full Waveform Inversion (FWI), provided significant uplifts in quality for detailed interpretation of seismic amplitudes.

A major difference compared to the previous case study lies in the thick succession of sub-parallel sequences from the overburden down to Triassic intervals, as illustrated in Figure 4. As expected, shallow water depths (around 80-90 m) and a near flat seabed complicate the processing and imaging of primary events whose structures were overlapping with multiples over large extents. In addition, a distinct chalk package with high reflective top and base interfaces generated extra weak periodical interference, mainly in the Jurassic interval. Although the amplitude of those internal multiple reflections is weak compared to water layer multiples, their impact on stratigraphic analysis and amplitude-driven interpretation becomes evident once the latter are well attenuated. Therefore, a comprehensive processing sequence including surface-related and internal multiple attenuation workflows was critical in providing necessary uplifts for CCS characterisation. When comparing the reprocessing to the legacy results, not only is thin layering much better resolved, but fault patterns are also much clearer and better reveal potential leakage pathways across the storage units in various intervals and through the seals.

The seabed and the first 200-300 ms showed distortion due to poor near-offset coverage, as shown in Figure 5. Similar to the first case study, separated wavefield imaging of the near-surface using primaries and multiples aided the processing itself, and effectively removed more interfering multiple energy (Oukili et al., 2015), and now provides a more complete image for overburden derisking (Figure 5).

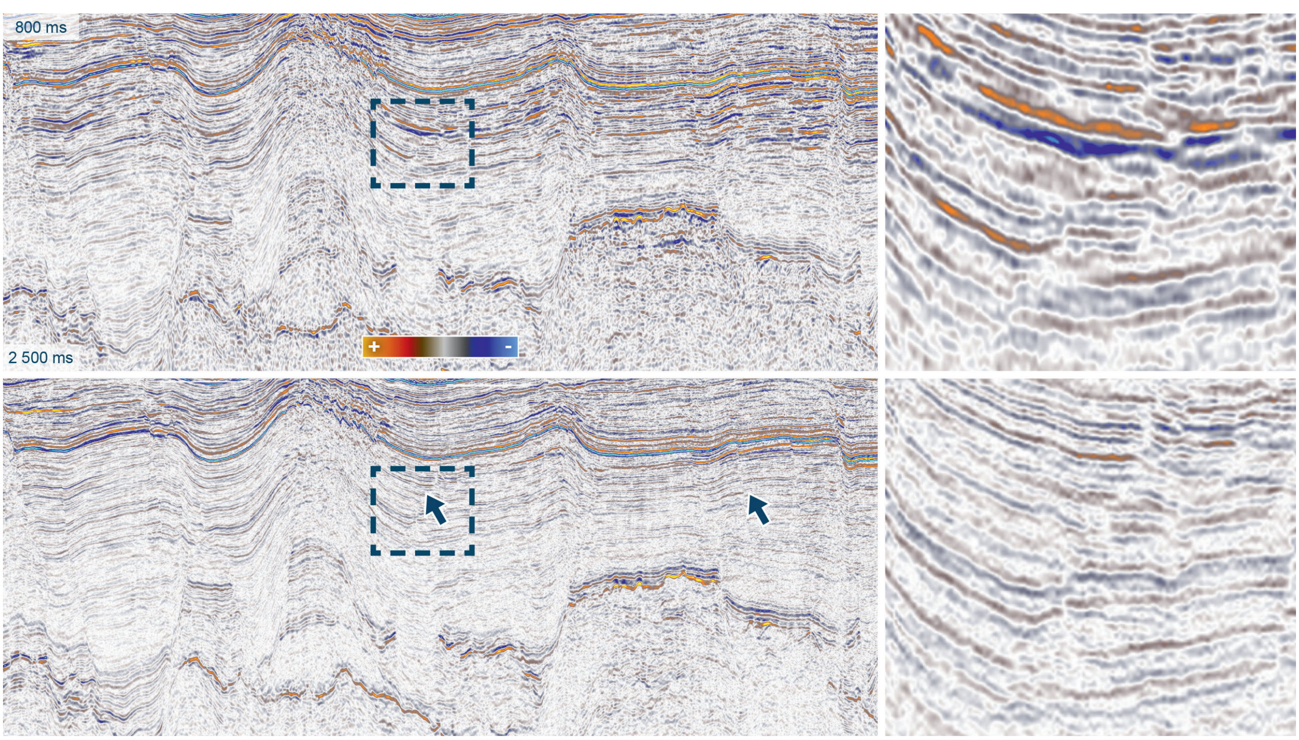

Figure 4 Intercept (2-term Shuey) volume from the 2013 KPSDM reprocessing (top) and 2023 reprocessing (bottom) illustrating the large successions of sub-parallel packages, from the chalk layer to Triassic units, with a complex Zechstein geometry in the lower part of the images. Residual surface and internal multiple reflections appeared with lower-frequency content and locally high amplitudes in the previous results. The new data show increased resolution, more accurate amplitudes and better clarity of faults, for example at the locations denoted by the blue arrows and in the crops (middle Jurassic intervals).

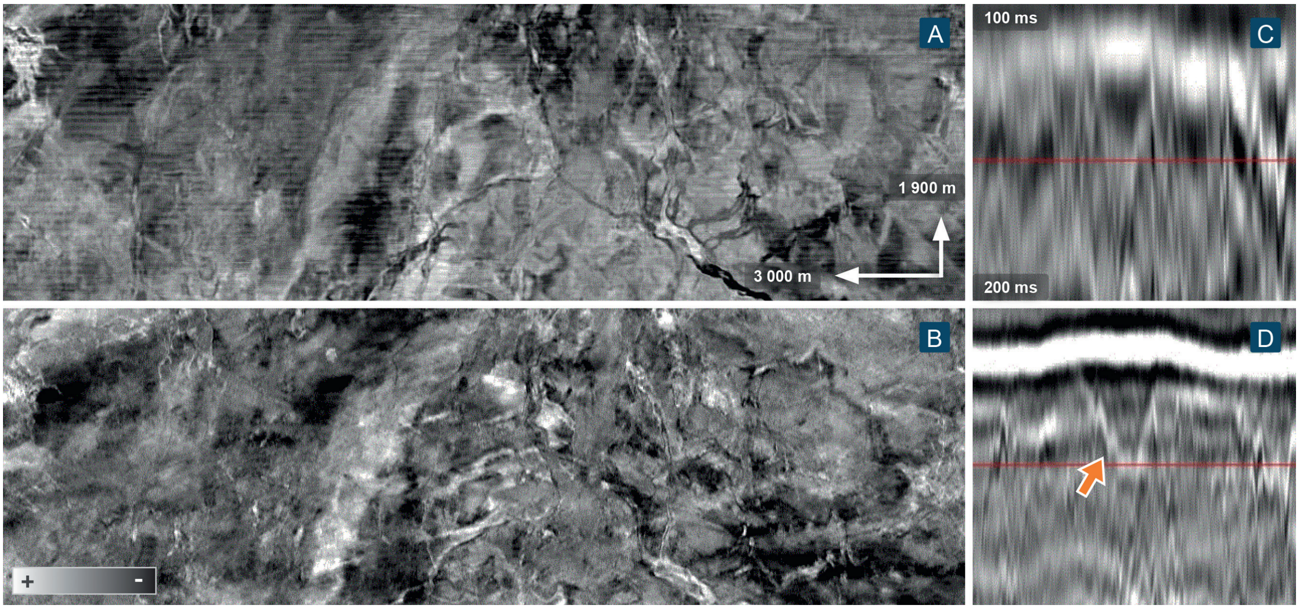

Figure 5 Time slices at 166 ms of the 2023 final KPSDM stack (a) and 2023 SWIM image (b). Acquisition footprint is no longer visible in the SWIM results. Many features appear different in the two volumes and can be explained by the cross-section displays, KPSDM stack (c) and SWIM (d), where many details are smeared in the KPSDM image (based on primary reflections only) and leave incorrect amplitude signatures, especially along the vertical axis. The SWIM image appears more accurate both spatially and vertically (arrow).

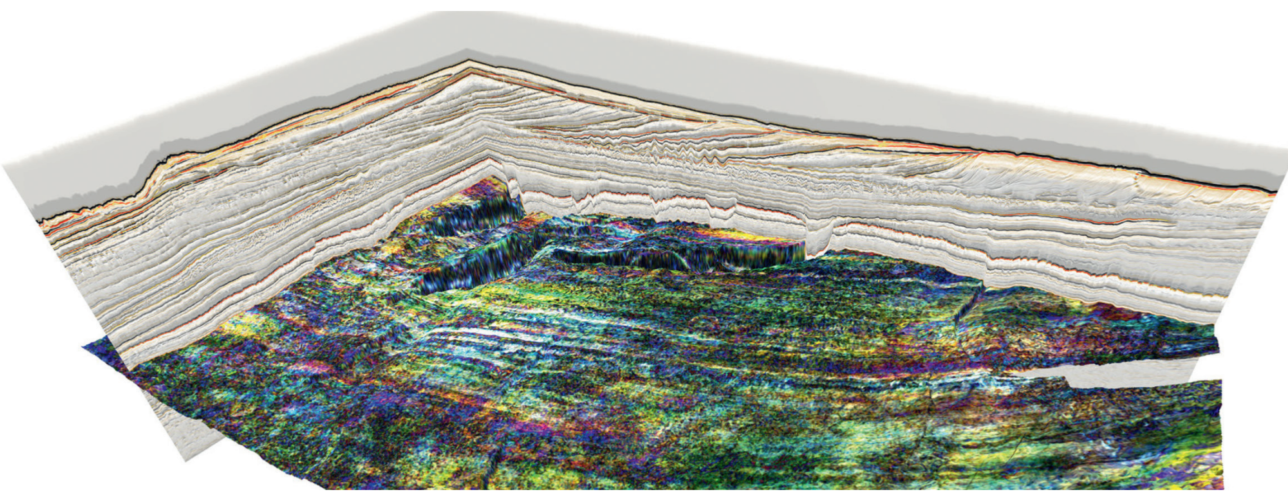

Figure 6 Chair diagram showing a combined spectral decomposition display from the Ile Formation aquifer highlighting the spectacular strand plain geomorphology that can be extracted from the Elephant seismic dataset. Understanding the depositional fabrics allows informed decisions to be made on the orientation of horizonal permeability distributions among other parameters, vital for understanding the behaviour of CO2 in the subsurface.

The prior processing efforts in 2013 achieved substantial improvement for gas exploration, where the requirements were somewhat more isolated and distinct in terms of detection and mapping of seismic amplitude anomalies. The CCS potential in this basin lies in the storage capacity over the thick units of sub-parallel layering where more comprehensive imaging becomes a necessity. Whilst further analysis may reveal the need for additional information and possibly the addition of newer seismic data, the time and costs associated with the extra processes applied in the latest imaging efforts are both insignificant and invaluable for this type of CCS validation project.

Developing new CCS concepts from modern high-quality seismic data

The third case study draws our attention to the Norwegian Sea, an area with continuing O&G exploration. In 2019, a large multi-client program employed a modern acquisition system with dual-sensor towed-streamer technology and a triple-source setup. Combining the triple-source setup with the high-density streamer spread geometry provided the necessary high level of subsurface detail, that could reveal the potential of the Trøndelag platform. The focus area is located east of the prolific basins of the Halten Terrace and Vøring basin, in intermediate water depth (around 250 m) and closer to the Norwegian shoreline.

The Elephant project, a metaphoric name associated with the actual outline of the survey which may as well represent its size and ambitions, utilises a very extensive (>10 000 km^2) high-quality PGS broadband GeoStreamer 3D seismic dataset. It is an excellent example of frontier CCS exploration in practice, where the area in question has not had significant success for petroleum exploration and is relatively sparse in well data. However, the quality of this seismic data is exceptional and ideal for assessing critical subsurface risks associated with storage site definition. The site itself is focused on up to four lower and middle Jurassic aquifer units and invokes multiple storage mechanisms (solution, residual/capillary, and local structural/stratigraphic trapping) to target a large gigatonne-scale potential storage site.

Lloyd et al (2021) demonstrated how integrated seismic-stratigraphic mapping can be used for effective seal assessment. Their workflow highlighted the need for high-resolution seismic data to effectively identify and map the immediate seal units overlying the aquifer with separate mapping for the remainder of the overburden (the units >50 m above the top aquifer surface). Figure 6 illustrates both the high-quality and the resolution of this data, which is sufficient to complete accurate and detailed mapping of the seal and overburden units above the top Garn, the uppermost store unit in the Elephant area. Toesets, onlaps and clinoform geometries can all be clearly identified in the overburden and assessed for their capacity to create configurations that might compromise integrity or create future bypass zones for any CO_2 that might migrate out of the complex into the overburden. Similarly, faults are extremely well imaged, and these can be mapped with confidence and their impact on top seal and overburden integrity confidently assessed. This data also demonstrates how attributes can be generated to create critical insights into other aspects of the store definition. Particularly relevant in data-lean saline aquifers is the ability to obtain reliable aquifer characterisation insights, which can then be used to constrain geological and simulation models.

Figure 6 shows the presence of a clear strand plain morphology within the Ile Formation, the next aquifer down from the Garn. Reliable ties to cored offset wells mean that integrated seismic and core data provide a robust understanding of reservoir characteristics that can then be applied with high confidence to geological modelling concepts, demonstrating that state-of-the art 3D seismic data and imaging have a crucial role to play in carbon storage site evaluation alongside more traditional methods.

Due to the higher requirements in seismic quality for exploration, especially in the near-field context, and thanks to significant advances in acquisition and imaging technologies, 3D data that have been acquired and processed in the most recent years are likely to be sufficient for CCS exploration, at least for concept development and screening purposes.

New acquisition designs and baseline considerations for future monitoring

As demonstrated by the case studies above, reprocessing of legacy seismic data can play a major role in CCS site screening and development. However, repurposing existing seismic data may not always be sufficient, especially if the legacy data was acquired with very different imaging objectives in mind, is poorly sampled, and does consequently not lead to a more detailed characterisation of the potential CO_2 storage site. Acquisition geometries for tailored new CCS marine seismic projects are constrained by the necessity to image the overburden including the near-surface and, in some cases, also by a shallow water environment. Advanced towing configurations that combine wide-tow multi-source configurations with multi-sensor streamers enable high-resolution imaging from the very shallow subsurface to deeper geological structures in a cost-effective manner. These modern seismic acquisition solutions, originally designed for hydrocarbon exploration with a focus on shallow reservoirs, have been quickly adapted for CCS development surveys (Figure 7) and on a smaller scale for ultra-high resolution 3D site surveys for offshore wind (Cooper et al. 2023; Widmaier et al., 2023).

The relatively shallow targets in typical CCS projects make it possible for new seismic surveys to routinely record the refracted wavefield needed for FWI velocity model building in addition to seismic reflections for reflection imaging. This can be achieved by using longer uniform streamer spreads or high-density spreads in combination with sparse streamer tails. Such solutions are feasible with neither significantly increasing survey cost nor compromising turnaround and have been deployed in recent CCS-related seismic surveys.

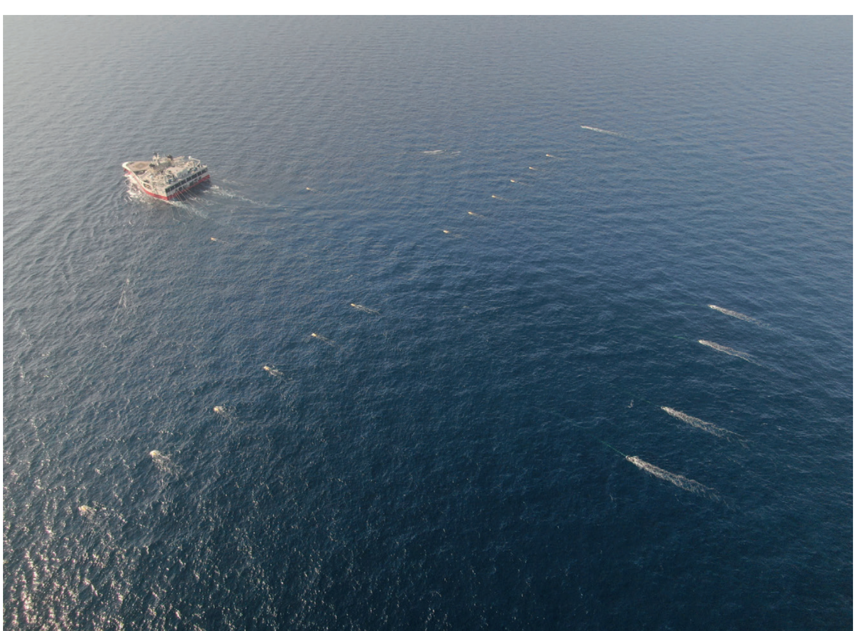

Figure 7 Ramform Atlas acquiring a high-resolution seismic survey for Aker BP (operator) and OMV over the Poseidon CCS licence in the Norwegian North Sea in 2023. The configuration consisted of 16 multi-sensor streamers (less floats than streamers) with 50-m separation and 6000-m length. The wide-tow quad source (floats on the right-hand side) was towed over the front end of the streamer spread.

In the longer term, CCS exploration and development surveys will likely serve as baseline surveys for seismic monitoring of the CO2 storage site. Seismic monitoring is key to detecting the migration of the CO2 in the reservoir and studying the integrity of the seal over time. Densely sampled baseline surveys that provide optimal sampling from near to far offsets can derisk future monitoring objectives and enable seismic monitoring methods based on high-resolution imaging, full waveform inversion, as well as quantitative interpretation. Traditional baseline surveys for monitoring of hydrocarbon reservoirs were often acquired with standard single or dual source arrays and short offsets only. Thus, direct experience transfer from hydrocarbon reservoir to CO2 storage site monitoring for wide-tow multi-source and longer offset streamer acquisition solutions are not necessarily possible. 4D repeatability and detectability requirements in the context of CCS are currently the subject of a major research effort in the industry with a rapid progress in technology development and improved understanding.

Conclusions

Today, seismic exploration for CCS benefits from both the historical data acquired for the O&G industry and the technological progress made for launching new, more complex offshore development projects. In north-west Europe these two industries work hand-in-hand in many areas already. However, there are divergences to be seen, most notably due to the fundamentals of the economics and the scale of currently planned CCS projects and their expected lifespan.

There is yet to commence a large dedicated CCS screening program, where the industry combines technology and resources from both traditional hydrocarbon exploration with the CCS effort for cost-effective screening of large and/or multiple sites. There is no doubt that CCS will play a critical role in achieving net-zero targets, albeit the negative public perception associated with the industry's own CO2 emissions needs to be addressed with more focused decarbonisation efforts. As such repurposing legacy data from traditional hydrocarbon exploration for CCS is less about shaping a positive legacy of the O&G industry and more about diversification and evolving the industry.

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