Seismic mini-streamers as a potential method for CO_2 storage monitoring

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Abstract

Carbon Capture and Storage (CCS) technology is recognised as an important contribution to mitigate climate changes, and monitoring of the injected carbon dioxide (CO_2) is an important element of this technology to ensure that the CCS system operates within the required legal and regulatory standards. To be able to offer more flexible monitoring solutions, the potential of mini streamers for overburden and shallow CCS monitoring has been investigated. The results from a series of 2D and 3D mini-streamer operations across the Sleipner CO_2 storage site are assessed and compared with conventional streamer seismic. The results show a clear enhancement in overburden imaging and higher detail at the CO_2 plume level compared to conventional streamer seismic data. However, the mini streamers also come with limitations related to the acquisition configuration (for example limited fold, offset, etc.).

Introduction

CCS technology has a vital role to play in mitigating climate change. The technology consists of capturing CO_2 at the source, such as power plants or factories, and storing it in underground formations. In recent years there has been a significant development in the deployment of large-scale CCS projects, demonstrating a growing recognition of the technology's ability to address climate change. However, the adoption of CCS needs a strong business case to be successful. To improve the business case, the technology, including monitoring cost, would benefit from becoming more mature and cost-effective. Monitoring is an essential part of the technology to ensure conformance and containment of the stored CO_2. Conformance monitoring involves demonstrating that the CCS system operates within the required legal and regulatory standards. The monitoring of conformance helps to minimise environmental and safety risks, which could otherwise have negative implications for public perception, operational efficiency, and legal compliance. Containment monitoring ensures that the CO_2 injected into subsurface formations remains securely stored within the storage complex, with minimal environmental risk. Therefore, through regular monitoring, the integrity of the storage facility is assessed and any potential leaks or escape points that could compromise the effectiveness of the CCS system are identified. In addition, regular monitoring helps to identify potential gaps in performance and assists in making informed decisions to improve the operational efficiency and prevent environmental and safety risks.

To date time-lapse seismic, using conventional seismic streamers, has been the main technology used to image and monitor the subsurface in offshore CO_2 storage sites (Furre et al., 2017). Here, we show how we have investigated mini streamers or Extended High Resolution (XHR) seismic as a potentially more flexible and cost-efficient solution for CCS monitoring.

While conventional streamer acquisition is characterised by a multitude of seismic streamers that are several kilometres in

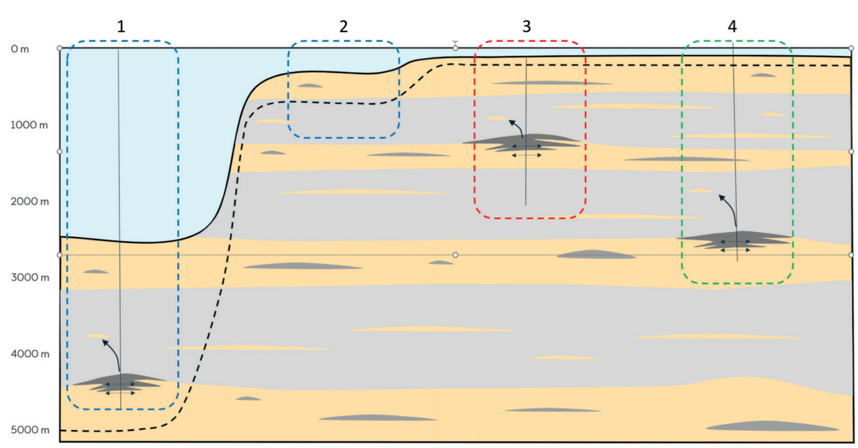

Figure 1 Illustration of different application scenarios for the XHR technology. Scenario 1 is similar to the deep-water GOM tests, Scenario 2 is similar to the Barents Sea experiment. Scenario 3 is the one that was investigated through this research and scenario 4 is left for further research.

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DOI: 10.3997/1365-2397.fb2024085

length, XHR uses significantly shorter streamers with a length typically ranging from tens to a few hundreds of metres.

Originally mini streamers were deployed successfully in the Barents Sea to map the Håkon Mosby Mud Volcano (Berndt et al., 2006) and later their use was demonstrated for time-lapse purposes in the Gulf of Mexico (GoM) to monitor two injection wells in a reservoir at 800-1200 m depth in 2500 to 3000 m water depth (Hatchell et al., 2019). In both cases, the targets were located above the first water bottom multiple. However, the potential for using this technology to monitor deeper targets in shallow water depth where the target falls below the first water bottom multiple was unclear. Figure 1 illustrates different scenarios for the application of the mini-streamers.

Short streamer seismic can potentially help to reduce monitoring costs, increase acquisition efficiency, and improve shallow data imaging, making it a suitable choice for offshore CCS shallow storage and overburden monitoring. It might also be used as a quick triggering inspection system in case other monitoring has implied non-conformance or non-containment, potentially saving a large time-lapse seismic acquisition. In addition, it has potential to be used in shallow water environments, in areas where access is restricted or in other areas where traditional streamers are impractical.

Equinor has extensive experience monitoring oil and gas fields, including several fields equipped with Permanent Reservoir Monitoring (PRM). Johan Sverdrup is one of the fields enabled with PRM, located approximately 50 km away from Sleipner (Fayemendy et al, 2021). The PRM operations at Johan Sverdrup include once to twice yearly acquisition of active seismic data using a dedicated modular seismic source deployed from a platform supply source vessel (Hibben et al, 2015).

In our study, the potential of utilising a seismic source vessel from PRM operations to acquire seismic XHR data on the Sleipner CO_2 field was investigated. This would not only enable the testing of the XHR technology for monitoring deeper targets (down to 2000 m) in shallow water areas (approximately 90 m) but also help evaluating the potential of using PRM facilities for other nearby operations to reduce the operational cost.

Initially two XHR 2D surveys, consisting of a series of 2D lines, were acquired in October 2020 and May 2021 respectively over the Sleipner CO_2 storage site, using a PRM source vessel. After promising results from the 2D surveys, a 3D survey was conducted in September 2022 across the site. The latter acquisition also incorporated a series of repeatability tests. These tests were then compared to conventional time-lapse seismic data across the same site.

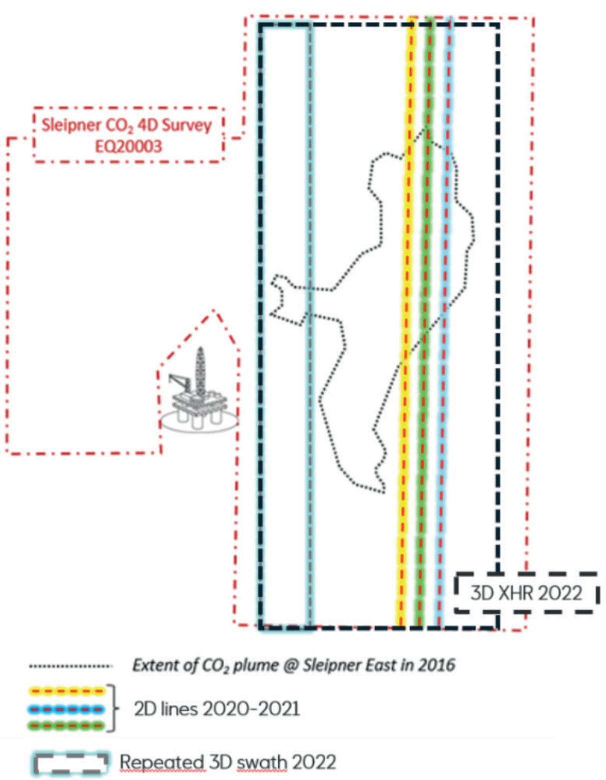

Figure 2 The map shows the coverage of different data acquisitions. Red is the conventional seismic survey from 2020, yellow, green and blue are the 2D-XHR lines acquired in 2020 and 2021, while black is the coverage area for 3D-XHR and grey is the coverage area for time-lapse repeatability test from 2022.

Sleipner-CO_2 storage site

Sleipner Vest field is a natural gas field located in the North Sea, about 250 km offshore the coast of Norway. The natural gas of Sleipner Vest contains high levels of CO_2 and this CO_2 has been captured and stored in the Utsira formation east of the Sleipner-Øst production platform. The Utsira formation is a saline aquifer at 800 m to 1000 m depth with a high porosity and permeability sandstone containing thin intra shale layers acting as a buffer for vertical CO_2 flow (Furre et al., 2017).

Over the past 27 years, more than 19 Mt (million tons) of CO_2 has been stored at Sleipner. Time-lapse seismic data has been an important tool monitoring the CO_2 plume over this time, with a total of 10 repeated conventional seismic surveys acquired to date. The CO_2 at this depth has a strong amplitude contrast to the brine-filled formation. Given the high amplitude contrast and the relatively shallow CO_2 storage reservoir makes Sleipner-CO_2 site a suitable candidate to investigate the benefit of mini-streamers for CCS monitoring. During the last 4-5 years the CO_2 injection has tapered off significantly due to reduced production. This means that we do not expect to see major changes in the development of the CO_2 plume, except potentially some internal rearrangements, with CO_2 migrating towards the top of the plume. The latest conventional survey was conducted in 2020, and the time-lapse changes during the XHR tests are assumed to be minimal.

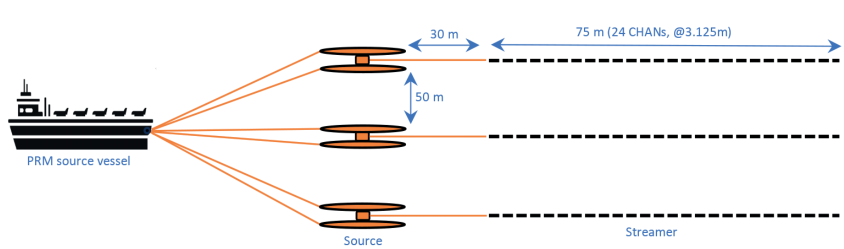

Figure 3 General acquisition layout for the 2D acquisition, indicating how three short XHR mini streamers (dashed black line) were deployed from the PRM source vessel and towed directly from one gun string of each of the three gun- arrays (orange).

Data acquisition

2D tests

Using the PRM source vessel from Johan Sverdrup, additionally equipped with an XHR mini streamer, a series of 2D tests were carried out in 2020 and 2021. A base line survey was acquired in October 2020 and a monitor survey conducted seven months afterwards in May 2021. With such a short period between base and monitor it is not expected to observe a visible time-lapse effect. However, the intention was to verify the repeatability of the technology. Three sail-lines were covering the eastern part of the CO_2 plume (Figure 2).

The XHR system consisted of three short streamers, each 75 m long, with a receiver spacing of 3.125 m (Figure 3). Each streamer was towed directly from one gun-string of the triple source array, with an array separation of 50 m, where each array contained two gun-strings. The two gun-strings in an array each had a gun volume of 900 cubic inches with only one gun-string activated for each source location. The streamers were towed at 6 m depth, the same depth as the gun strings, with a minimum offset of 30 m from the last gun in the array. Each source-streamer pair was considered a separate 2D line and sail-lines were acquired in a flip-flop-flap fashion, with a shot point interval of 12.5 m effectively producing a source interval between consecutive shots for each array of 37.5 m, which provided an effective fold of one. This geometry led to a bin grid with 1.5625 m inline and 12.5 m crossline dimensions. The sampling interval for the streamer was 0.5 ms.

3D and time-lapse repeatability tests

A 3D field trial, consisting of 36 prime lines covering a 5x2.5 km^2 rectangular area over the Sleipner CO_2 plume, was conducted in September 2022 (Figure 3). Additionally, five repeated lines were acquired in the western part of the survey (Figure 3) to assess repeatability.

The XHR system this time consisted of 12 streamers each 150 m long, with a receiver spacing of 3.125 m and 12.5 m streamer separation where the streamers were towed at 11 m depth (Figure 4) deployed from a vessel of opportunity. The vessel employed for this operation was the Sanco Atlantic, which exceeded the required size for this test. However, it was deemed the most suitable option for conducting the complete set of experiments scheduled for this operation. The source consisted of dual 880 cubic inch arrays towed at 5 m with a source separation of 6.25 m operating in flip-flop mode with a nominal shot point interval of 6.25 m. The bin grid for this 3D geometry had dimension that were 1.5625 m inline and 3.125 m crossline and a fold of six.

Data processing

2D and 3D image processing

Conventional streamer surveys typically involve large offset ranges, large source volumes, and deep tow depths for both sources and streamers. In contrast, site surveys usually have shorter offset ranges, smaller source volumes, and shallower tow depths for both sources and streamers. The acquisition geometries for the 2D and 3D XHR field trials differed from these conventional and site surveys, featuring short offset ranges, large source volumes, and deep tow depths for both sources and streamers, which required stringent quality control.

Given the unique acquisition spread, it was critical that small errors in positioning for both source and streamer were controlled for and corrected. Also, with a relatively large source volume and short offsets, much effort was given to the source de-signature process incorporating both de-bubble and de-ghosting. While swell noise attenuation, seismic interference and tidal statics were addressed, extra close attention was paid to the de-multiple process. The details of XHR data processing are shown in Figure 5.

Previous applications of mini streamers had seen relatively shallow subsurface targets compared to water depth, which eliminated the need for de-multiple for such short-offset data (Hatchell et al., 2019 and Planke et al., 2010). At the Sleipner CO_2 storage site the water depth is approximately 90 m and the Utsira formation depth ranges from 800 to 1000 m, combined with the short offsets of the XHR data, requires the need to effectively perform of de-multiple. A combination of two model-based de-multiple techniques, 3D Model-based Water-layer De-multiple (MWD) and 3D Surface-Related Multiple Elimination (SRME) was

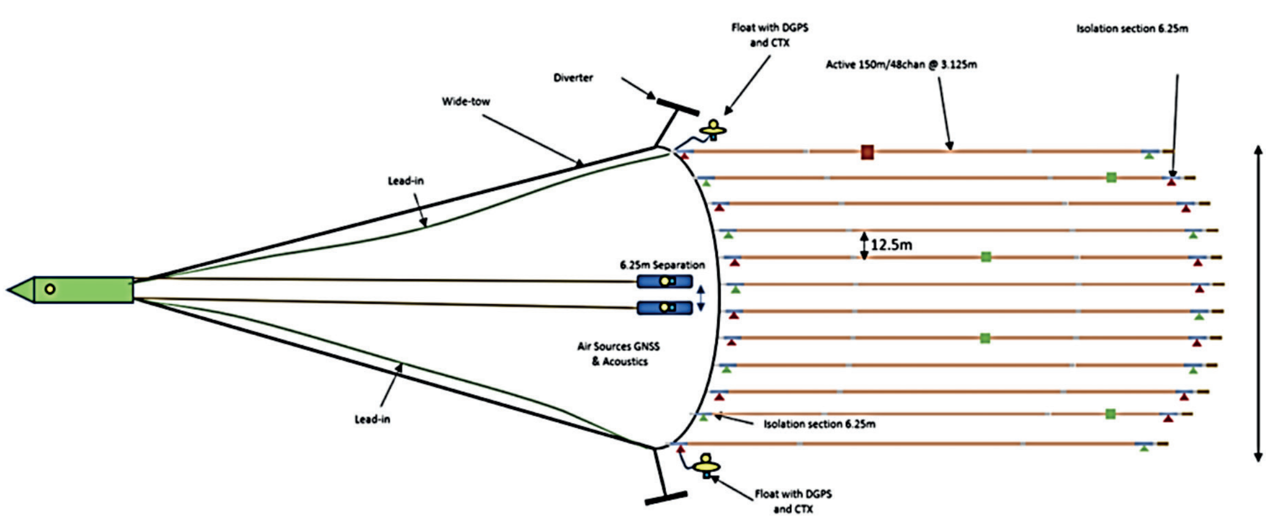

Figure 4 Plan view of the XHR spread used for the 3D field trial. Twelve streamers were used, each 150 m long and towed with 12.5 m streamer separation.

applied to handle multiple subtraction. A regional velocity model was used as an initial velocity model in the FWI workflow up to 15 Hz, which was subsequently updated to 60 Hz using the XHR data. The resulting velocity model was used for the Pre-Stack Depth Migration (PSDM) of the XHR data. Some more details of this processing were published by Ryan et al. (2024).

Time-lapse repeatability

The repeated test, from the 2022 3D survey, consisted of five prime acquisition sequences and five repeated sequences recorded two days later. The repeatability processing steps considered the initial swath of five acquisition sequences a baseline, and the five repeat sequences as a monitor. The processing sequence applied for the repeatability test was based on the sequence used in the main 3D processing with the addition of time-lapse specific steps.

An important step was 4D binning with both the baseline and monitor binned onto 1.5625 m (crossline) and 6.25 m (inline) subsurface grids and traces with source and receiver location variations (DsDr) more than 50 m were discarded before regularisation (Figure 6).

Additionally, spectral matching between monitor and base was applied where global spectral amplitude and phase matching operators were derived between the base and the monitor and applied to the monitor dataset.

Observations

2D and 3D

Figure 7 compares conventional seismic data acquired in 1994 (prior to injection start), in 2020 (the latest conventional repeat) with three sets of XHR data (2D from 2020 and 2021, and 3D from 2022). Blue represents a hardening (e.g. the seabed at approximately 100 ms) and red a softening (e.g. the CO_2 plume within the yellow rectangle). The main features (e.g. the strong seabed and CO_2 plume reflections) are visible in all datasets, but there are also some notable differences.

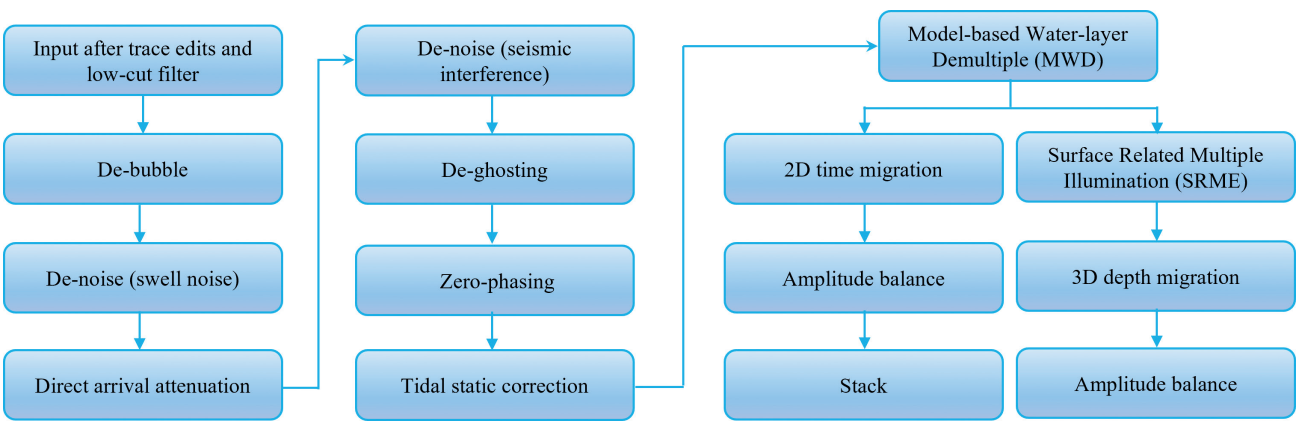

Figure 5 Overview of the main processing sequences applied to 2D and 3D XHR data. The two processing sequences were equal until the model-based water-layer demultiple (MWD) and deviated afterwards.

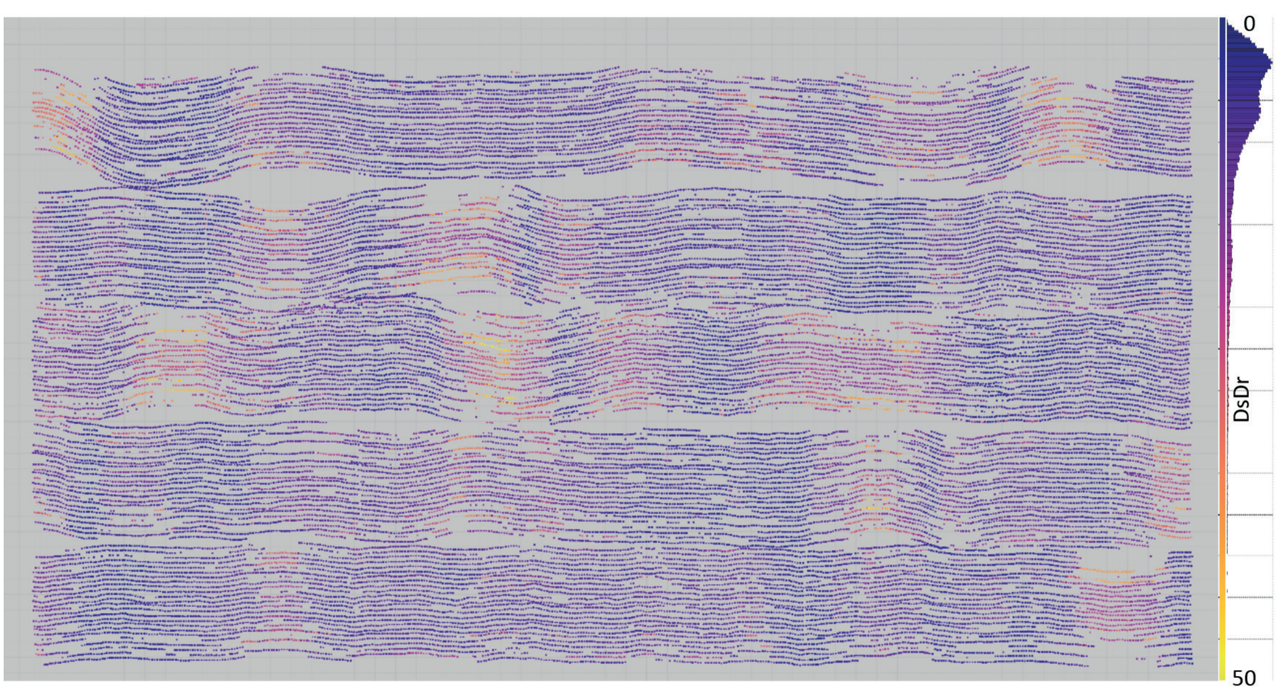

Figure 6 Midpoint map of monitor classes after 4D binning with DsDr clipping. The colour bar indicates the DsDr values (0-50 m range).

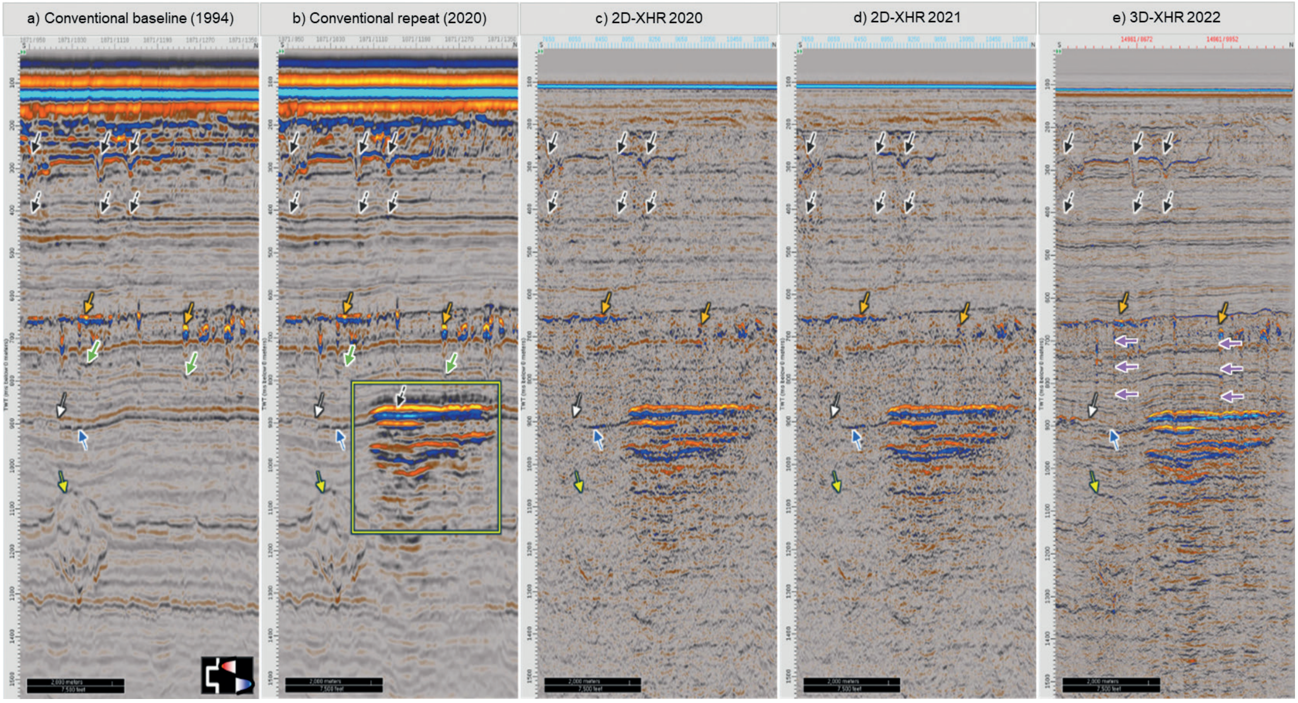

Figure 7 Seismic sections corresponding to the yellow 2D line in Figure 2. a) Conventional baseline (1994), b) Conventional repeat (2020), c) 2D XHR 2020, d) 2D XHR 2021, e) 3D XHR 2022. The seismic sections have been visually balanced to match the conventional 2020 time-lapse repeat. A decrease in impedance is defined as a red (soft) amplitude. White and yellow solid arrows indicate the location of the top and base of the Utsira storage unit. The CO_2 plume shows up as the strong amplitude reflections within the yellow rectangle. The black solid arrows show the area improved in XHR such as glacial valleys while dashed black arrows show the vertical disturbances in the reflections in a deeper area compared with the same reflection in the conventional seismic. The orange arrows show strong amplitude anomalies in the overburden, believed to be related to gas in overlying layers. These anomalies were already in place prior to CO_2 injection start. The green arrows show the reflections due to seabed multiples from these and the purple arrows show the disruptions related to pushdown features below the primaries which appears more pronounced on the XHR than on the conventional data. The white and yellow arrows show the weak reflections at the top and base of the Utsira storage unit while the blue arrows show the features that are not well-resolved in the XHR data.

In general, the XHR datasets exhibit greater resolution, being sharper with more details, albeit with higher noise levels (especially for the 2D data). In particular the shallow overburden section (100-200 ms) is much better resolved in the XHR data than in the conventional data, while slightly deeper (250-350 ms) glacial valleys are visible in all datasets (black solid arrows), though with some disturbances below (black dashed arrows), which are most pronounced in the 2D XHR data. Deeper down and for weaker reflections (e.g. between 300-600 ms), not all reflections are as continuous in the XHR data as they are in conventional seismic data.

Note how the time interval from 640-750 ms is characterised by stronger amplitudes, including several strong red over blue amplitude pairs with. These are known from the wider regional area and have been attributed to thermogenic or biogenic gas migration, accumulation, and biodegradation over geological time (Nicoll 2011). These soft amplitudes are observed in both the conventional and 3D XHR datasets, but not all of them are present in the 2D XHR data. Beneath these soft amplitude anomalies, there are also indications of disrupted signals. In the conventional datasets, there are notable reflections with opposite amplitude to the primaries and an arrival time in accordance with the expected first order seabed multiple (green arrows in Figure 7).

In the 3D XHR dataset the disruptions appear more like bands of pushdown features below the primaries (purple arrows in Figure 7). These coincide with pushdowns at the top of the CO_2 layer (purple arrows in Figures 7 and 8).

In the section down to the top of the CO_2 plume most of the reflections are comparable between the conventional and 3D XHR data. However, weaker reflections at the top and base of the Utsira storage unit (white and yellow arrows) are not as well-resolved in the XHR data, while a shale near the top of the storage unit (blue arrows) is still clearly visible (Figure 7).

The CO_2 plume is clearly visible in all repeated seismic sections, and the XHR reflections are sharper and better at resolving the top and base of the CO_2 layers than the conventional dataset is capable of. Note how the XHR data has identified an extension of the CO_2 that is not observed in the conventional data, as shown by the red arrow on Figure 8. This is attributed to CO_2 flowing towards the top of the plume resulting in a slight extension of the topmost layer.

Time-lapse Repeatability

Normalised Root-Mean Square (NRMS) has previously been calculated for prior conventional surveys, using a time window between 500 and 800 ms (Furre and Eiken 2014), representing an interval above the CO_2 plume, where it is assumed that time-lapse changes related to CO_2 injection will not affect the calculation. NRMS calculations were also carried out on the XHR data from the 2D 2020 and 2021 repeated lines and the later 3D 2022 time-lapse repeatability tests.

The 2021 and 2022 XHR datasets, acquired with one year separation, not fully repeated, led to NRMS values of around

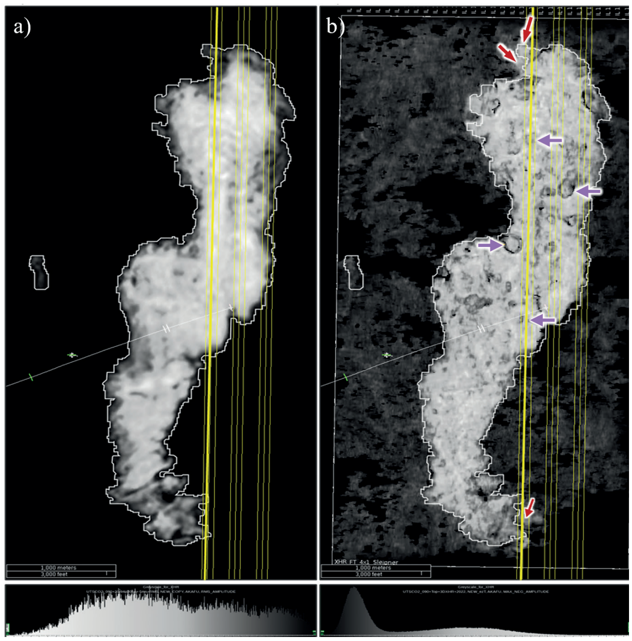

Figure 8 Time-lapse amplitude maps representing the uppermost CO_2 layer: a) RMS (Root-Mean-Square) extracted from conventional difference data (1994-2020) in a time interval +/-5 ms around the trough corresponding to the top of the Utsira storage unit; b) Maximum Negative Amplitude extracted in the same time interval from the 2022 XHR data. Colour scales, though not directly comparable, are tuned to display similar signal strength between the datasets, with lightest colours representing the strongest amplitudes. The yellow lines show the 2D seismic lines, with the thicker line representing the location of the sections in Figure 7. The white polygon delineates the interpreted extent of the CO_2 plume from the RMS map in a), while red arrows highlight locations where the XHR data indicates a slightly larger CO_2 plume extent in 2022 than in 2020. Purple arrows highlight areas of delayed signal or pushdown below overburden anomalies.

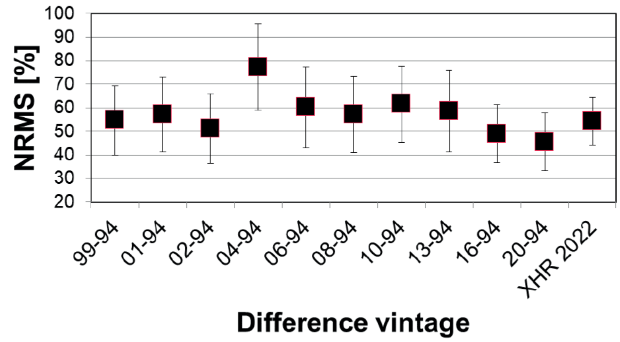

Figure 9 NRMS calculated in the overburden above the Utsira Fm (an interval between 500 and 800 ms) for the conventional time-lapse repeats and compared to the XHR 2022 time-lapse repeatability test.

65%. A high cut filter was applied to the 2D XHR data matching the frequency content to the conventional 2020 data, which resulted in reducing the NRMS to approximately 35%. The 2022 3D XHR survey, with five lines immediately repeated using the exact same acquisition parameters and similar weather conditions, showed an NRMS of approximately 54%.

The values for NRMS seen by the XHR data were similar to those observed with the conventional surveys acquired between 1999 and 2020 (Figure 9).

Discussion

XHR technology, with its short offsets, relatively large source size, deep tow for both source and streamers, and low fold, falls somewhere between conventional towed-streamer and site survey technologies. However, there were concerns about its ability to monitor deeper targets in relatively shallow water depths due to issues related to repeatability, multiple attenuation in shallow waters, and general limited offset ranges.

Despite these concerns, the results of the study demonstrate the potential of XHR data to provide higher resolution and more detailed information, particularly in the shallow overburden section and down to the CO_2 plume. Although the XHR data exhibited more noise than conventional seismic data, metrics for repeatability were comparable to previously acquired conventional datasets, especially when the frequency content for the XHR was brought more into line with the conventional data (Figure 9).

From a data processing perspective, the deeper tow depths for the source and streamer required extra attention, and the limitations of XHR data, which stem from the short offsets inherent in the technology, were initially a concern. The limited offset range of the XHR data makes it susceptible to water bottom multiples, which can obscure the signals from deeper targets. However, this concern was largely addressed through a careful application of model-based de-multiple techniques. The lack of long offsets limits the ability to build velocity models, especially when Full Waveform Inversion (FWI) is considered. This was mitigated by using a velocity model derived from a legacy streamer dataset.

While the XHR data provided higher resolution and more detailed information than conventional seismic data, it was subject to undesired pushdown artifacts, most likely related to the limited offset range of the data, which limits the ability to undershoot shallower disruptive features. Furthermore, for deeper and weaker reflections, these reflections were not as continuous in the XHR data as they were in conventional seismic.

It's worth noting that this study focused on the ability to image the CO_2 plume at Sleipner and reused legacy data where appropriate, with no attention given to amplitude versus offset and describing petro-elastic properties of the subsurface. Future uses for XHR should carefully consider the requirements for offset information and the need to complement XHR with other measurements.

Conclusions

Field trials of the XHR technology were performed on the Sleipner CO_2 field, firstly in 2D utilising a PRM seismic source vessel and later in 3D with a dedicated vessel to investigate the potential of this technology for CCS monitoring. Considering the initial concerns related to the short offsets inherent with XHR, the data was successfully processed, interpreted and compared against legacy data.

While the limitations of the XHR data, due to the short offsets, should be recognised, the trials found that the XHR data has good potential to offer more detailed information in the shallow overburden section and down to the CO_2 plume compared to conventional seismic data. In addition, time-lapse tests showed that the XHR data can have comparable levels of repeatability to the conventional data.

Use of XHR, for monitoring, requires careful consideration of necessary offset information and the need to complement XHR with other measurements.

Acknowledgements

The authors would like to acknowledge the Sleipner licence operator Equinor Energy AS and Sleipner licence partners PGNiG Upstream Norway AS and Vår Energi ASA for permission to publish the results. We acknowledge TGS for the PRM source operations and Viridien (formerly CGG Services) for processing the seismic XHR data and Gassnova for partial financial support of the operation through CLIMIT program.

The views and opinions expressed in this paper are those of the authors and are not necessarily shared by the licence partners.

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