Combined OBN and High-resolution 3D Streamer Acquisition for CO2 Monitoring: Initial Model Building and Imaging Results over Sleipner

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Summary

We present the results of a high resolution, hybrid Ocean Bottom Node (OBN) and short offset streamer (eXtended High Resolution, XHR) acquisition, combined with an enhanced processing solution to image the Sleipner CO_2 storage plume.

The XHR data provides high-resolution images of the shallow, including the CO_2 plume, while the OBN data provides long-offsets for velocity model estimation using FWI. The results demonstrate the potential of this approach for CO_2 monitoring.

Introduction

Carbon Capture and Storage (CCS) is an essential element of the drive to net-zero CO_2 emissions. Confirming storage integrity and tracking CO_2 plume movement are key components of CO_2 monitoring, particularly when the storage layers are thin and form a multi-layered setting (Martinez et al, 2023), however projects are often resource limited, and therefore any monitoring solutions need to be carefully planned and implemented to ensure viability.

Combining ocean bottom nodes with high-resolution, short-offset streamer seismic, offers a cost-effective solution, whilst overcoming the limitations of short offset streamer acquisition, enabling detailed velocity modelling work to be conducted and the implementation of advanced migration techniques.

In 2022 a field trial of this hybrid acquisition method, covering an area of 15 km^2, was undertaken over the Sleipner CO2 storage facility offshore Norway.

Method

The survey design was conducted to ensure the imaging potential of the seismic data but also to maximize the efficiency of the acquisition:

As part of the trial process, node deployment was planned on a 500 m x 525 m grid – individual nodes were equipped with a self-recovery mechanism and tracking beacon prior to deployment via a free fall approach.

To ensure suitability of the deployment method, statistics on relative node positions to pre-plot location were computed, with a median distance of 3.9 m.

The node data was recorded simultaneously with the XHR data by utilizing the shots fired from the streamer vessel to form the shot carpet. In this way, offsets up to 5 km were acquired. All nodes were later recovered with no components remaining on the sea floor following completion of the acquisition.

Deploying, acquiring, and recovering the OBN dataset in this way has the advantage of eliminating the need for a remotely operated vehicle (ROV) during the acquisition, this reduces turnaround time and cost both of which are key drivers when considering CCS solutions.

The XHR acquisition was planned with the primary objective of imaging the CO_2 storage plume, specifically the Utsira formation (c. 800 m) (Pedersen et al, 2017), however imaging of both the overburden and under burden were also included as secondary objectives – to achieve this, the XHR streamer data was acquired at 1 ms sample rate, 150 m maximum offset, and 3000 ms record length. A narrow streamer spread (12 x 12.5 m) and dense shot grid provides a bin size of 1.56 m x 3.125 m, which is required to image small-scale faulting and the thin shale layers of the Utsira formation into which the CO_2 is injected. Cables are towed at 11 m to enhance low frequency signal response.

The source arrays were equipped with dual depth near field hydrophones (Kryvohuz & Campman, 2017) to complement and enhance the signal processing of the XHR data.

A series of trial lines, designed to evaluate potential improvements to acquisition, were also acquired including node shot lines with 10 km maximum offset, a line of 100 m node spacing, and a series of source volume tests (Figure 1).

In total from mobilization to final closedown, the acquisition was completed over a period of 30 days.

Pre-processing of the XHR dataset is designed to maximize resolution, to achieve this an evolutionary processing workflow (EvoFlo) is used. Data is initially processed using a nominal sequence, including: deghosting, Surface Related Multiple Elimination (SRME), regularization and PreStack Time Migration (PSTM) to enable evaluation of results in the image domain.

Areas for improvement are identified; refinements and additions are made to the processing workflow to target the identified improvements – this process is iterated multiple times to ensure the best image is achieved.

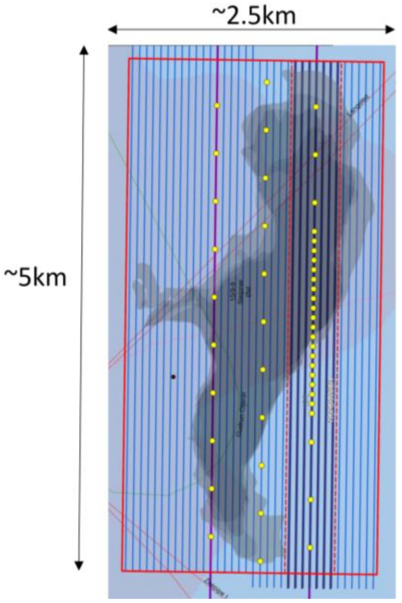

Figure 1: Acquisition layout of the Sleipner CO_2 monitoring survey. Sail lines / OBN source lines in blue, additional test lines in purple & OBN locations in yellow. Plume extent is shown underlying the acquisition.

For the latest EvoFlo application, environmental and SI noise are removed from the dataset prior to application of source and receiver inversion deghosting to extend the usable bandwidth of the dataset. Shot by shot designature - using far field signatures derived from the dual depth near field hydrophones - is followed by receiver X-Y repositioning and an iterative 3D SRME & Internal Multiple Elimination (IME) application to suppress the strong multiple content that cuts across the primary reservoir targets. 4D Anti Leakage Fourier Transform (4D ALFT) is used to regularize the dataset prior to a Pre Stack Depth Migration (PSDM) outputting a 1 m depth step to maximize the resolution of the seismic image.

Velocity model building is performed on the OBN dataset, taking advantage of the long offsets that are not available on the XHR dataset. The initial velocity model is derived from 2D data spanning the survey area that is subsequently converted to a 3D volume (figure 2), the extracted volume is smoothed prior to well calibration, the water column velocity profile is based upon T-S dip profiles acquired over the duration of the survey.

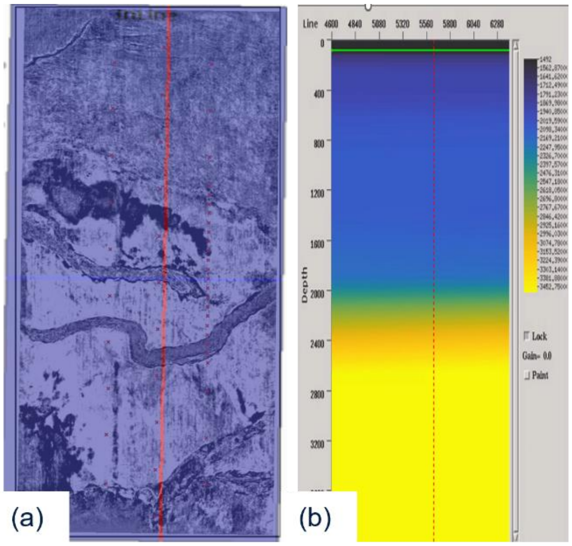

Figure 2: Velocity model prior to FWI at a depth of 232 m overlain on XHR PSDM data (a) and section view (b) of velocity model.

Raw hydrophone node data is used to perform diving wave full waveform inversion (FWI) up to a frequency of 12 Hz, utilizing the NFH dataset within the FWI workflow. Node data processed through up-down deconvolution (UDD) is used for high frequency reflection FWI updates. Joint inversion of the XHR and OBN dataset is also planned for later work.

The FWI model is used to image the XHR data with an anisotropic Kirchhoff PSDM with an additional RTM planned, but FWI will also be run up to higher frequencies to evaluate the benefit of high-resolution imaging with FWI.

Results

Figure 3 shows the results of the latest EvoFlo processing sequence on the XHR dataset compared to a conventionally acquired legacy 3D volume. The resolution of the overburden is enhanced on the XHR dataset, multiple energy suppression is good with subsequent improvements in imaging of shallow channel features not seen in the conventional seismic image.

The CO_2 plume is imaged well with the individual layers clearly visible in the larger overall structure, lateral continuity of individual events and structural details are also enhanced compared to the conventional image.

Figure 4a shows the latest FWI velocity update cutting through shallow channel features at a depth of 232 m, velocity slowdowns associated with channel infill correlate with the seismic image in the southern portion of the survey area, with structural highs to the north pick out through a velocity increase. Bifurcation of the central channel is also resolved via the FWI. Injectites at a depth of 600 m (figure 4b) are also modelled, the associated structural imprints on the CO_2 plume corrected for with the PSDM data.

Within the primary plume target (figures 4c & 4d), the reservoir layers are clearly imaged on the XHR data, the FWI derived velocity model details clear velocity slowdowns associated with the CO2 relative to the surrounding geology, variations both vertical and lateral are also identified in the velocity model.

Reflection FWI is expected to add additional detail to the velocity model, further constraining the plume extent and enhancing the definition of the individual layers within the structure.

The final imaging results show that the high resolution XHR dataset is enhanced with velocity model building methodologies only available using the long offset, sparse OBN dataset; the imaging uplift is significant without impacting costs due to the employed hybrid acquisition.

Conclusions

A high resolution, hybrid OBN and streamer acquisition combined with an enhanced processing solution successfully images a CO_2 plume and surrounding sediments at the Sleipner field. Both high-resolution imaging and long offset velocity model building are made possible through this hybrid acquisition method and workflow. Given the economics of carbon capture and storage (CCS), cost-effective solutions are required. This work shows that XHR acquisition combined with OBN data can be an integral component of 4D monitoring solutions for CCS.

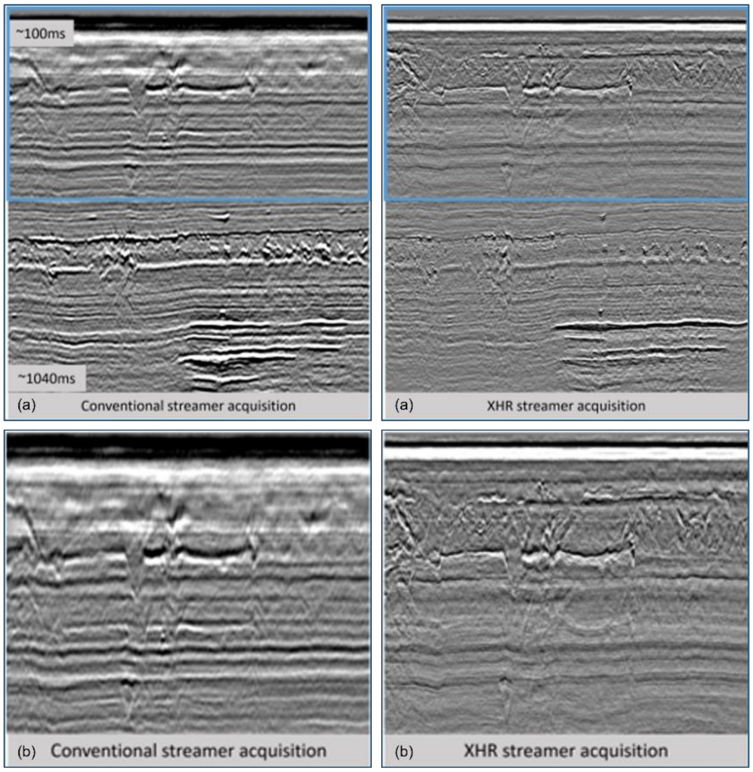

Figure 3: Section view comparing conventional streamer (left) and XHR streamer (right) acquisitions down to plume level (a) and shallow zoom (b). Enhanced imaging is observed throughout the section on the XHR image

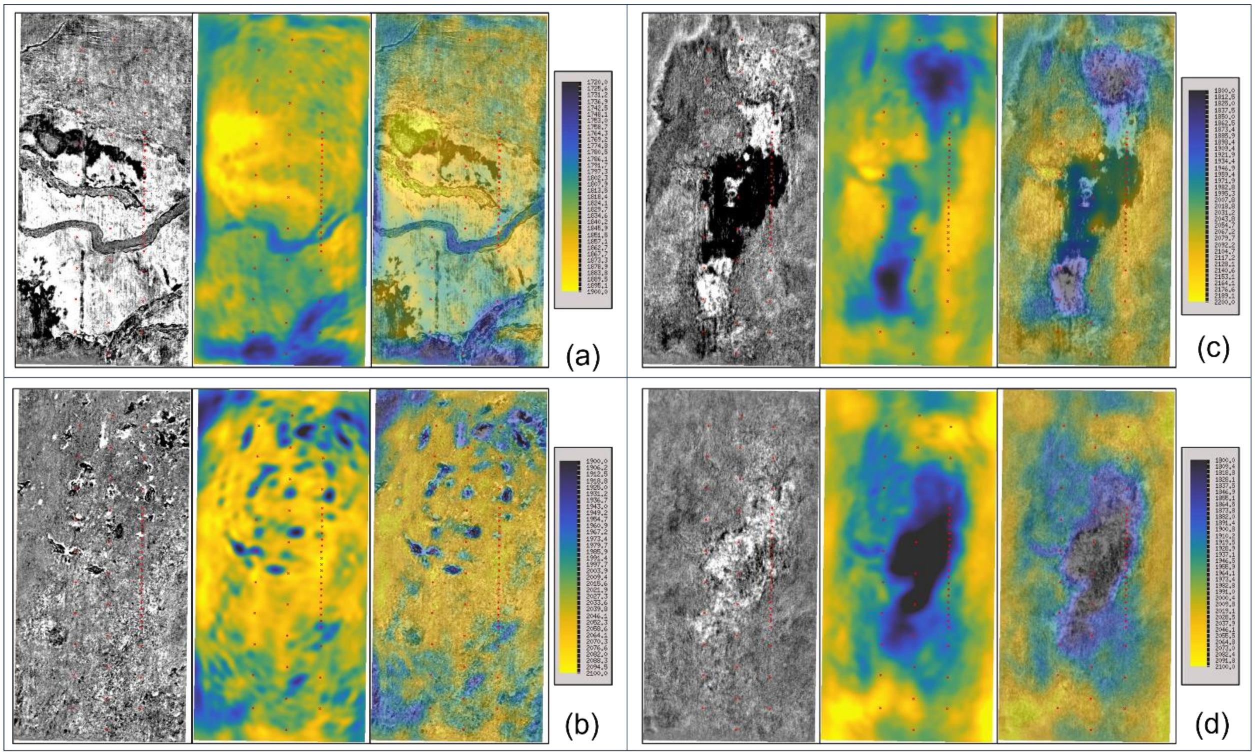

Figure 4: Depth slice using XHR data (left), FWI velocity model (center) and hybrid (right) views at 232 m (a), 600 m (b), 842 m (c) and 928 m (d). Channels and injectites are identified and constrained on the shallow slices, with the plume structure and associated velocity inversions constrained in the deep.

Acknowledgments

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