2023 EAGE ANNUAL
84TH CONFERENCE & EXHIBITION
VIENNA | AUSTRIA

Assessing the Processing and Imaging Challenges of DAS VSP Data for CO2 Storage Imaging and Monitoring

M. Galyga[1], H. Moore[1], S. Mannem[1], C. Bossy[1], R. Dehghan-Niri[2], P.A. Olsen[2]

[1] CGG; [2] Equinor ASA

Summary

We discuss challenges of Distributed Acoustic Sensing (DAS) data in a Vertical Seismic Profile (VSP) setting and propose processing and imaging solutions to overcome these. The context is to review processing challenges and benefits of DAS VSP as a potential cost-effective solution for CO2 storage monitoring. DAS VSP data acquired during a monitor surface seismic acquisition over the Johan Sverdrup field in 2021 provides the means to assess this, with both learnings and uncertainties from this study informing on the potential of this technology in other geological settings. Here, an initial feasibility assessment conducted using a baseline and repeat monitor survey, acquired a few weeks later, indicated the achievable levels of repeatability with this data type. An inclusive pre-processing flow and use of both up-going and down-going wavefields in a tailored imaging routine showcases the level of subsurface illumination and high signal-to-noise levels for 3D reservoir imaging. Finally, subsequent CO2 modelling work provides an understanding of the potential of DAS VSP surveys for future 4D monitoring work for conventional or un-conventional reservoir monitoring.

Assessing the Processing and Imaging Challenges of DAS VSP Data for CO2 Storage Imaging and Monitoring

Introduction

A current challenge facing the carbon capture and storage industry is the ability to monitor the reservoir at a CO2 site in a cost-effective and accurate manner. The method of Distributed Acoustic Sensing (DAS) in a Vertical Seismic Profile (VSP) setting is one possible solution, offering the opportunity to acquire low-cost and frequent time-lapse surveys to monitor changes in reservoirs, as demonstrated by Yu et al. (2022). To demonstrate this and evaluate areas of further development, a 3D and 4D DAS VSP test was performed over the Johan Sverdrup permanent reservoir monitoring (PRM) system (Figure 1). Johan Sverdrup is one of the key fields on the Norwegian continental shelf, and it has been instrumented with several technologies to optimize oil recovery. Among these are the fiber optic Ocean Bottom Cable (OBC) system installed in 2019-2020 and DAS fibers installed in several wells to monitor well activity. Availability of these solutions during an ongoing PRM monitor survey provided an opportunity to test DAS VSP processing capabilities and gain unique knowledge to process these data. A 3.3km long single-mode, standard DAS fiber cable was interrogated as the acquisition vessel acquired PRM data. Obtained experience can provide valuable insight and streamline the processing efforts of any DAS VSP dataset with the purpose of cost-effective CO2 monitoring solution.

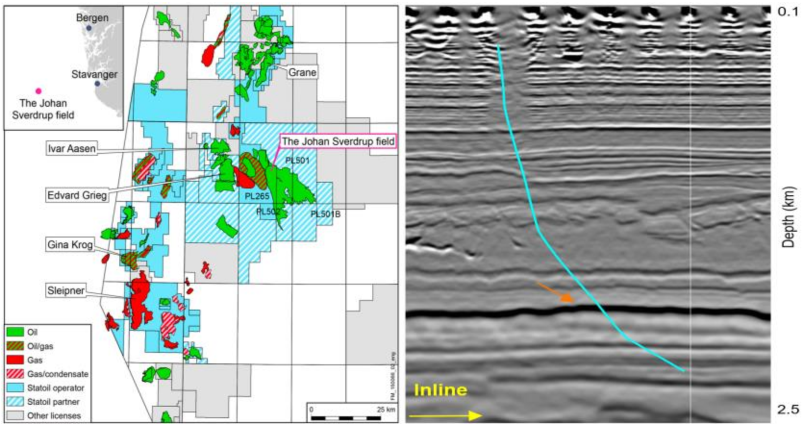

Figure 1 *The Johan Sverdrup field location and a seismic section through the field showing the platform hole and the trajectory of the well in which the DAS fiber is clamped (blue curve), through the strong chalk layer (highlighted by the orange arrow) and into the deeper reservoir package*

Initial repeatability assessment and pre-processing

In addition to the processing of a 36 square km shot carpet from an ongoing PRM survey, an additional six sail lines of data were acquired three weeks later to provide an auxiliary dataset with which an initial assessment of repeatability could be conducted. However, the large deviation of the wellbore in conjunction with the limited illumination provided by the small surface coverage meant image domain analysis was sub-optimal. In addition, this auxiliary dataset was acquired during water injection and thus exhibited a notable increase in noise content compared to the main dataset. Despite this, repeatability analysis undertaken in the data domain following a Deep Neural Network (DNN) based de-noise workflow (Moore et al., 2022) highlighted the high levels of repeatability that could be achieved with DAS VSP data, even during injection. Additional processing, including 3D source de-signature using Near Field Hydrophone recordings and a Green's function based 3D Model-based Water-Layer De-multiple, were also included prior to analysis in the image domain. These imaged results (Figure 2), despite being laterally limited, gave confidence in the subsequent work of 3D imaging and CO2 modelling.

3D imaging of up-going and down-going wavefield

With pre-processing work completed, imaging was conducted for the up-going and down-going wavefields separately to provide a high-resolution image of both the deeper thin reservoir packages and the overburden channels, respectively. The large velocity contrast (approximately 2500 m/s) at the top chalk event made the sub-chalk imaging of the reservoir package particularly challenging. A ray-traced variable aperture centre Kirchhoff (Figure 3b) was utilized for the up-going wavefield to provide full bandwidth imaging with a significant reduction in migration swings compared to Reverse Time Migration, the more conventional imaging algorithm for this acquisition type.

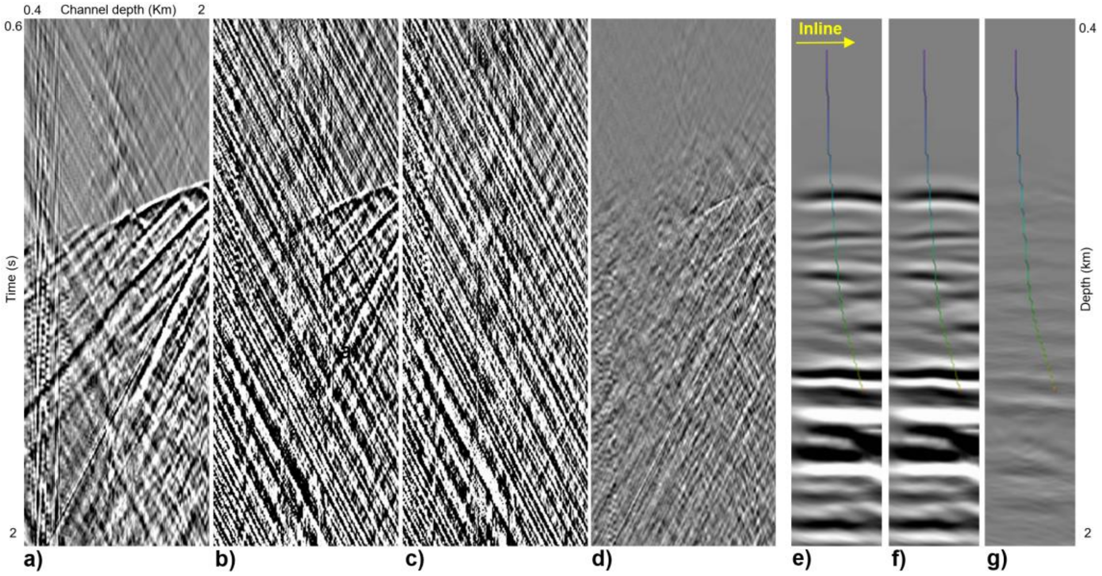

***Figure 2** Mid-offset shot displays: a) Baseline data, b) Monitor data showing strong linear noise originating from the water injection, c) the raw 4D, and d) the 4D following a Deep Neural Network de-noise workflow with the majority of non-repeatable noise well suppressed. Up-going migration displays: e) baseline data, f) monitor data following the DNN de-noise and g) the 4D difference highlights the highly repeatable signal achievable despite this limited processing.*

Despite this, the 3D image still suffered from high-amplitude stretched energy believed to be originating from strong refracted arrivals from the Top Shetland event, which contaminated the deeper interval. These events arrive with a large range of angles into the DAS receivers in this VSP set-up, particularly given the high deviation of the wellbore. To overcome this, the source and receiver side opening angles were calculated from travel time gradients within the migration and a limit of 52.5 degrees was imposed. This effectively suppressed these strong arrivals (Figure 3c), providing a clearer image, particularly below the Top Chalk, as well as limiting the extent of the imaging to areas of high confidence.

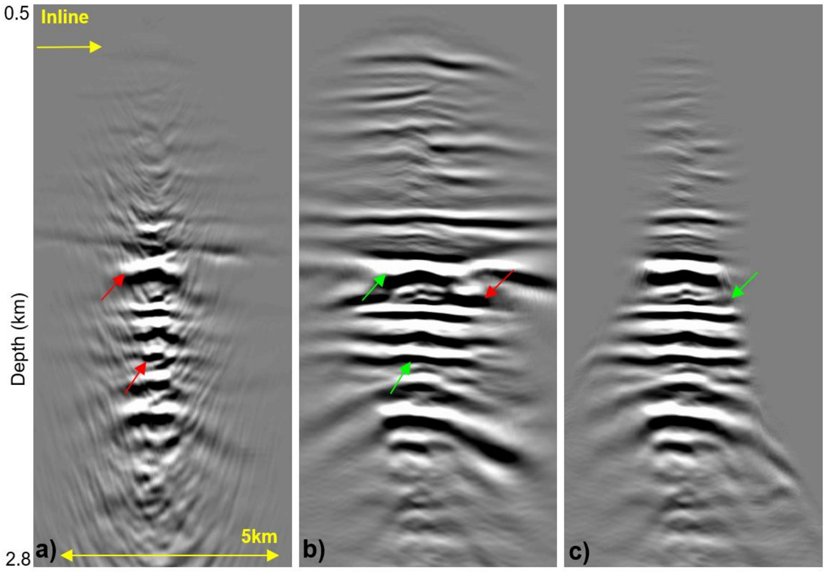

***Figure 3** Migrated crossline displays: a) Reverse Time Migration of the up-going data showing notable migration swings cross-cutting the top chalk event and deeper base reservoir event (red arrows), b) Variable-aperture centre Kirchhoff with reduced migration swings (green arrows) but strong refracted energy still present (red arrow), and c) inclusion of an opening angle limitation improving event clarity below the top chalk (green arrow) and defining the area of reliable signal.*

This optimized up-going imaging provided a reliable high-resolution image of the chalk and reservoir packages but exhibited limited coverage of the overburden. For this purpose, multiple imaging using the down-going wavefield was implemented as a solution to improve the overburden illumination in this shallow water setting. To achieve this, Reverse Time Migration of Multiples (Moore et al., 2021) is a proven methodology, but the de-convolution imaging condition is subject to cross-talk, where different orders of surface scattering can contaminate the image. As such, an alternative approach, based on the least-squares wave-equation multiple migration (LS-WEMM) method with a causal and anti-causal cross-talk suppression, as described by Poole (2021), was used. Figure 4a shows a conventional Reverse Time Migration of Multiples approach exhibiting the strong cross-talk energy present throughout the migrated section, which makes clear event identification challenging. Results with this LS-WEMM based method in Figure 4b show a notable improvement in signal-to-noise ratio (SNR) throughout the section, with high levels of spatial and temporal resolution compared to the legacy PRM data. Subsequent merging of the up-going and down-going wavefield images provides a continuous image through the overburden and into the reservoir package.

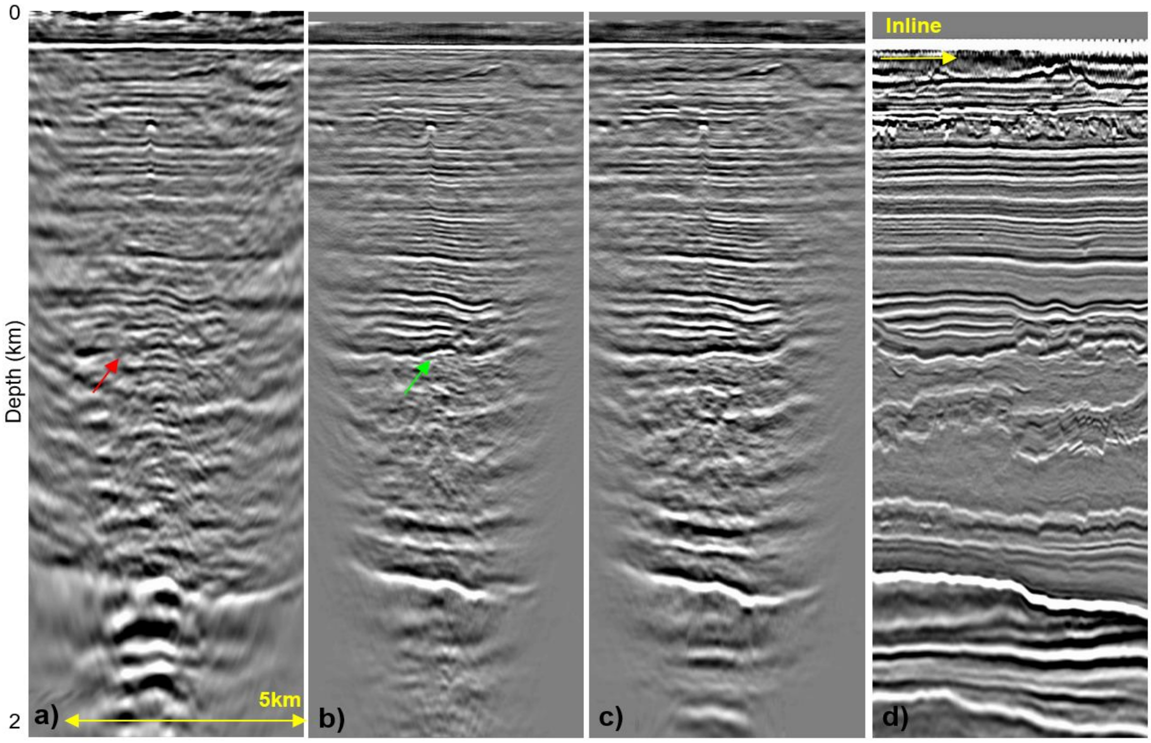

Figure 4 *Image domain displays: a) A conventional Reverse Time Migration of Multiples approach exhibiting strong cross-talk contamination (red arrow), b) the LS-WEMM approach showing improved event continuity (green arrow) and SNR. Merging with the up-going imaging c) highlights the achievable illumination coverage utilizing both wavefields and the high resolution achievable when compared with d) the PRM up-going image, which was used to validate the DAS VSP results.*

Time-lapse modelling and assessment

4D modelling was performed to further assess the processing flow for applicability to detect CO2 injection effects and assess 4D signal repeatability using a designed workflow. To this extent, a modelling exercise was conducted to distinguish the amplitude and time shift effects separately due to the presence of a hypothetical high-contrast CO2 reservoir. To accomplish this, a legacy velocity model was first modified with a 20% increase along a thin (20m) interval following a consistent geological layer at approximately 1.4km depth, in-line with a CO2 response from a typical 10% CO2 storage at this depth. Synthetic modelled shot gathers were then created via acoustic wave-equation modelling using both the legacy velocity model and this modified model, with a consistent density model obtained from the PRM reflectivity. Time and amplitude matching operators were then derived separately from a least-squares fitting between these two synthetic datasets in a window covering a full shot gather, before being applied to the raw data to simulate the recording of the CO2 4D response. The full pre-processing and imaging workflow for the up-going wavefield was then conducted for both approaches, with the aim of both providing a measure of sensitivity to these 4D effects via ratio of root mean squared amplitudes (RRMS) and cross-correlation metrics (Figure 5).

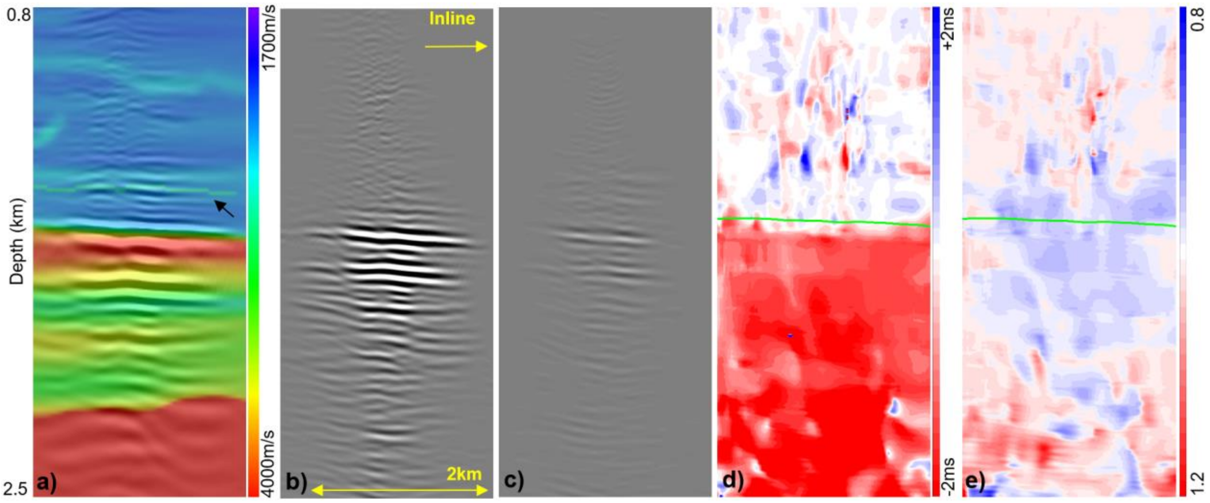

Figure 5 *Crossline displays: a) the P-wave velocity model, overlaid on the 3D DAS VSP up-going stack, that has been modified with an increase in velocity (black arrow) representing a reservoir with 10% saturation increase along the highlighted interval, b) 4D difference from application of time shift only operator and c) 4D difference from application of amplitude only operator to raw data as well as corresponding d) windowed cross-correlation time shift values and e) RRMS values calculated between the base and monitor suggest that the time shift caused by this CO2 inclusion (at the green overlay) is easily identifiable whilst the amplitude variation is of similar levels to background noise.*

Conclusions

The emergence of fiber-optic technology in a VSP setting as an attractive potential tool for overburden and reservoir imaging comes at an exciting time for both the conventional and un-conventional industry. However, the sensitivity of the DAS fiber leads to questions on repeatability measurement, whilst highly complex illumination patterns of up-going reflections make 3D imaging a challenging prospect. We have shown that a repeatable signal can be achieved even in injecting wells through the use of a dedicated de-noise and processing workflow. In addition, the combined use of up-going imaging via limited aperture Kirchhoff migration and down-going imaging via Multiple Imaging with Cross-Talk Attenuation provides an extensive yet reliable 3D image. Subsequent time-lapse modelling shows the potential in this approach for detecting and analyzing 4D differences caused from a CO2 reservoir.

Acknowledgements

The authors thank the Johan Sverdrup license operator Equinor ASA and partners Petoro AS, Aker BP ASA, and TotalEnergies EP Norge AS for their permission to share these results. The views and opinions expressed in this abstract are of those of the operator and are not necessarily shared by the license partners.

References

Moore, H., Galyga, M., Lowney, B., Kaszycka E., Lesnikov, V., Merry, A., Mitra, A., Taylor, D., Bellahsene, R., and Verliac, M. [2022] Optimizing of a DAS VSP image for 4D assessment at the Culzean field. *82nd EAGE Annual Conference & Exhibition*, Extended Abstracts.
Moore, H., Iliev, I., Drummie, S., Kaszycka E., Lesnikov, V., Merry, A., Mitra, A., and Verliac, M. [2021] Processing and Imaging of a DAS VSP Pilot Survey at the Culzean Field. *6th EAGE Borehole Geophysics Workshop*, Extended Abstracts, BG10.
Poole, G. [2021] Least-squares multiple imaging constrained jointly by OBN and Towed-streamer data. *82nd EAGE Annual Conference & Exhibition*, Extended Abstracts.
Yu, G., Zhao, Z.H., He, S.M., Zhang, X.L. and Chen, Y.Z. [2022] Monitoring Dynamic Changes in Reservoir Production using Time-Lapse Walkaway DAS-VSP Data. *First Break*, **40**(2), 31-40.