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High Frequency 3D FWI at Sleipner: A Closer Look at the CO2 Plume

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Summary

The 3D methods to monitor the CO_2 distribution at the Sleipner injection site have mostly been based on time-migrated image results. Full waveform inversion methods have also been applied to the problem with some success. However, the contribution to the characterization of the CO_2 plume was limited, because the applications were restricted to 2D data or to low frequencies only.

Based on recent improvements, we apply a 3D acoustic FWI with up to 48Hz to the marine 2010 dataset with the aim to better resolve the details in the plume and to improve the image directly below it. We achieve a significantly higher resolved velocity model where at least seven layers can be discerned. A vertical low velocity structure is visible, which is at the same place as the main CO_2 distribution chimney. And the location of the injection point is consistent with the strongest velocity anomaly below the CO_2 plume. A PSDM image based on the updated velocity model shows significantly less depth error at the Base Utsira horizon than with a previous model.

Introduction

Equinor has been running CO_2 Capture and Storage (CCS) projects for many years and is developing related monitoring technologies for future applications (Ringrose et al, 2018). A critical part of CCS projects is reservoir monitoring to ensure safe and secure storage of the CO_2 – to satisfy the regulatory requirements of conformance and containment.

At the Sleipner injection site, the CO_2 has been monitored by repeated seismic surveys for many years (Furre and Eiken, 2014). Most of the published studies investigating elements of Sleipner CO_2 reservoir monitoring use seismic stacks after pre-stack time-migration (PSTM). Relevant structural parameters such as number of CO_2 layers, the thickness, and extent of layers are estimated from this input. Further work concerning estimates such as CO_2 seismic properties, flow properties or fluid saturations is typically also based on the PSTM stacks in conjunction with well data.

While PSTM is a robust imaging technique, it nevertheless relies on some strong assumptions, e.g. small lateral velocity variations, and an additional conversion step when it is necessary to work in depth. Although the Sleipner injection site has a relatively simple overburden, there are however complications, such as channels in the overburden, that might significantly affect the PSTM image. The assumptions are probably also violated for deeper parts of the CO_2 plume located in the Utsira sand formation, resulting in imaging distortions for deeper parts of the plume. In addition, fluid flow predictions will likely depend on the accuracy of the time-to-depth conversion (Zweigel and Hamborg, 2002).

Several papers investigate more advanced imaging techniques such as tomography/depth imaging or full waveform inversion (FWI) to produce better images in depth and/or velocity models that could be used directly as attribute for further analysis (see e.g. Queißer and Singh, 2013, Romdhane and Querendez, 2014, Raknes et al, 2015). Common in all these studies is the focus on the reflective part of the wavefield due to the limited offsets in the pre-2010 streamer data. In addition, in all examples some type of velocity analysis has been performed to create an initial velocity model that contains the low wavenumbers of the model to enable the use of a least-squared (L2) FWI scheme.

In our case study, we use the pressure component of the dual-sensor marine dataset acquired in 2010 (Furre and Eiken, 2014) with larger offsets, which enables the use of diving and refracted waves in the FWI. Using an initial 1D velocity model, the objectives are: to investigate whether a 1D initial model is sufficient, how well FWI can determine the extent and inner structure of the CO_2 plume, and whether the resulting images for the lower part of the plume and below improve compared to previous results.

During the study it became clear that the result would benefit from separating the task into two phases. In the first phase we focus on estimating a medium-frequency background model based on long-offset full data, while in the second phase we refine this model with short-offset reflections based on the use of high-frequencies.

Phase One FWI

Only a few preconditioning steps have been applied to the seismic dual-sensor dataset: Trace edits, swell noise attenuation, and tug noise removal (possibly a minimum phase correction). The seismic data was reduced to every 7^{th} shot giving an effective shot distance of 87.5m. As initial model, we use an isotropic 1D model with a constant gradient from the seabed down to ca. 800m, and a constant velocity for the deeper part.

For the inversion part, we used an acoustic time-domain FWI code and switched between two different cost functions – a workflow strategy that has been tested before (Ravaut el al, 2017). For the first lower frequency bands, up to 10Hz, the cost function is based on Wiener coefficients – adaptive waveform inversion (AWI) – as presented by Warner and Guasch (2016). This reduces any problems due to cycle skipping when the initial model is too far away from the correct model. For higher frequencies, when the maximum frequency is beyond 10Hz, we switched to the standard L2 cost function, if we were sure that the data is not cycle skipped. When using the AWI cost function, there is no illumination compensation, while for the L2 cost function, the diagonal part of the Hessian is used to precondition the gradient. For the AWI iterations, we used a constant mute at 4 sec. For the FWI, we applied a soft mute to avoid reflections from below the Utsira formation and a top mute to avoid noise above the first arrival.

In the Phase 1 workflow, we used maximum frequencies up to 23Hz with offsets up to 4.5km down to a maximum target depth of 1.5km. In addition, we used frequencies up to 31Hz to improve the resolution for the shallow channels down to a depth of ca 350m. Further increases in inversion frequency did not improve the results in Phase 1 significantly.

In the final velocity model of Phase 1, the CO_2 plume appears as a heterogeneous low-velocity structure with several layers that are partially separated (Ringrose et al, 2018). Horizontal slices of the velocity model show that the low-velocity anomalies correlate well with amplitude-anomalies caused by the CO_2-layers in the time migrated seismic data (see Figure 1).

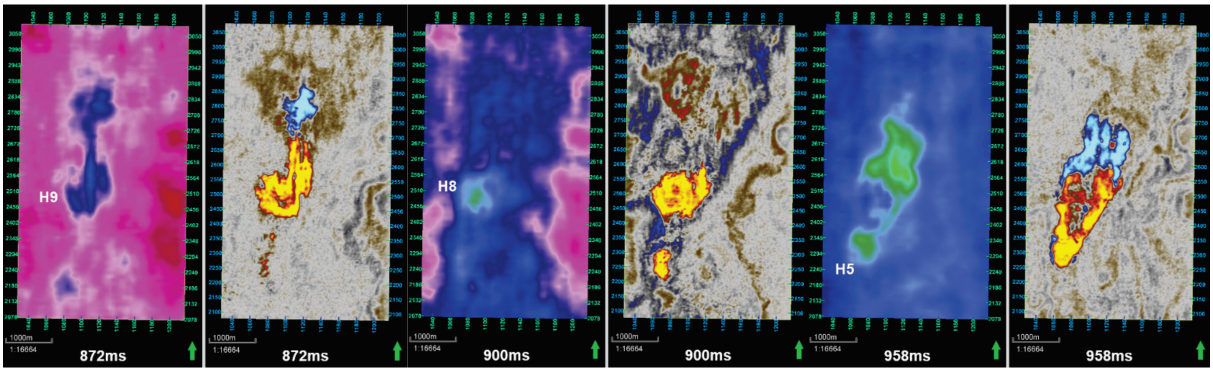

Figure 1 *Constant Time slices with instantaneous amplitudes around three selected CO_2 layers at vertical travel times of 872ms, 900ms, and 958ms. For each time slice, the left image shows the Phase 1 FWI velocities (after depth-to-time conversion) and the right image shows the 2011 HiRes PSTM.*

At this stage we found that the velocity anomaly connected to the injection point (well 15/9-A16) appears ca 60m too deep, which is twice as much as can be explained from anisotropy analysis. Also, the Base Utsira reflection has still a significant push-down effect and image gathers are curved downwards, all indicating that the velocity in the plume is significantly too high.

Phase Two FWI with Synthetic Study

To address the two main problems – too low resolution and too high velocity in the plume – we constructed a synthetic case using a lower-frequency version of the velocity from Phase 1. Altogether nine elongated cuboid low-velocity perturbations of -300m/s (three over each other) with three different thicknesses of 10m, 20m, and 40m were added. Using the L2 FWI with reflection data up to 2km maximum offset and some tuning of the weighting and illumination parameters, it was possible to detect and separate the 10m cuboids from each other with a five-band frequency approach using a final maximum frequency of 48Hz. However, the results still showed too high velocities between the cuboids and an increasing depth error for the deeper cuboids.

The depth error is caused by the fact that neither the initial model nor the seismic data contain enough information about the low-frequency part of the velocity perturbation. Typically, one would use ray tomography methods to estimate this part of the velocity model. However, the strongly distorted wavefield below the plume makes picking of the primary reflection events difficult. We instead decided to remove the positive velocity changes of the incorrect FWI update and then smooth the remaining negative changes. This approach is applied in or near the plume, where we can be sure that (almost) all velocity errors are negative due to *a-priori* information and/or due to the results from Phase 1. With the corrected initial model, we applied the Phase 2 workflow again and the result exhibits significantly reduced artefacts and a reduced depth error.

Following the successful approach for the synthetic data, we applied the same workflow to the real data – applying the changed FWI workflow and the estimation of the background correction. For the real data, we do not know exactly the strength of velocity perturbation, so in an additional step we run a few tests to determine the scale of the background correction. In the end, the final isotropic velocity model was further corrected for anisotropy. Using markers from well 15/9-13, we estimated a constant anisotropy model, which was used to rescale the velocity model to create a final velocity model.

Discussion of Final FWI Results

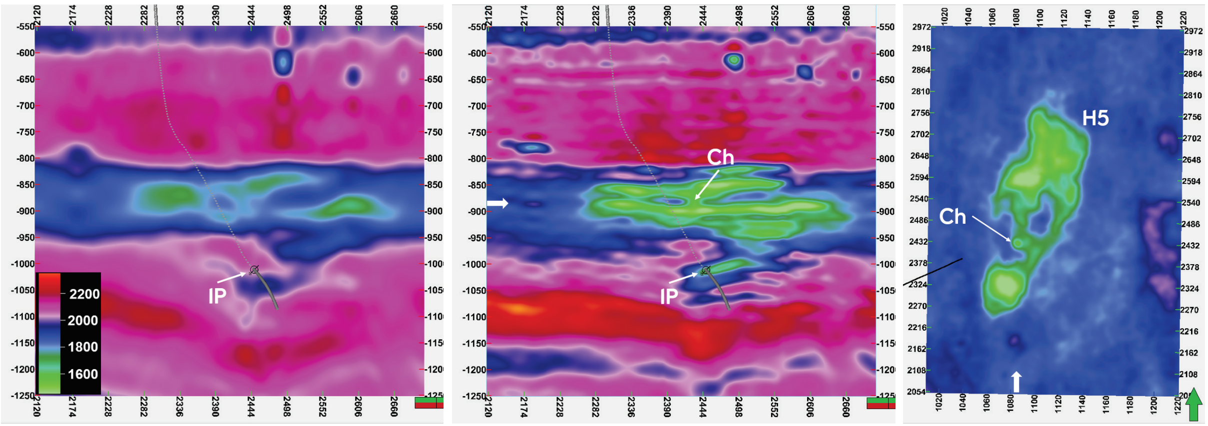

Figure 2 *(Left) Zoomed inline in depth at injection point (IP) of Phase 1 velocity model and, (Middle) Phase 2 velocity model (both after anisotropy correction), (Right) constant depth slice at 885m which also shows the point-like structure (Ch). The white arrows mark the slice positions.*

The final Phase 2 velocity model shows significantly more details than the Phase 1 model (Figure 2, left and middle images). The CO_2 plume itself sits within the Utsira sand formation that, when brine filled, has a ca 150 to 200 m/s lower velocity than the shale section above it. The separation between the two formations in the velocity model coincides well with the seismic observations. The Utsira formation thickness varies between ca 200 to 250m, and at the base, the velocity increases again before a ca 50-100m thick high velocity section appears in the FWI model.

In the plume, several layers are visible, and they are better separated than in the Phase 1 result. The CO_2 layer thicknesses vary between ca 10m and 20m; e.g. the two partially separated layers in the bottom part have thicknesses of ca 12m. Also visible is a chimney-like connection between the middle layers,

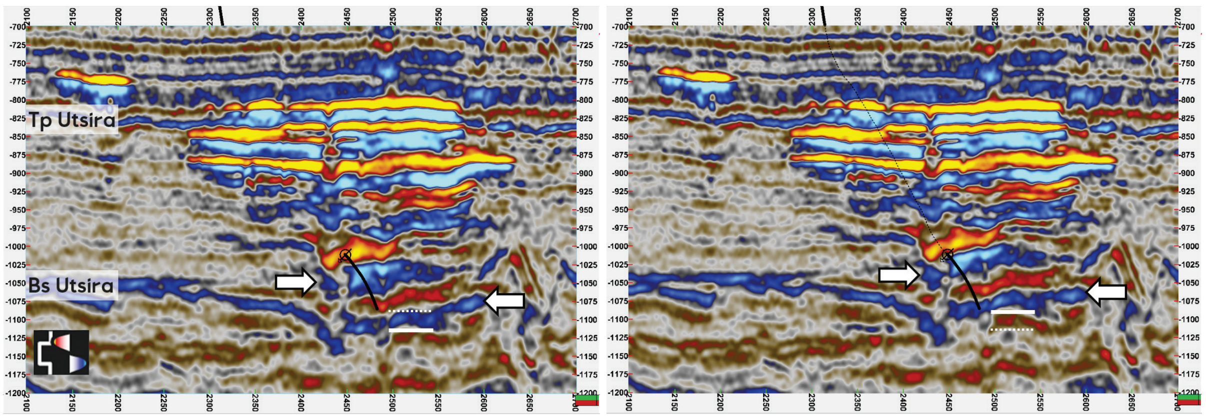

Figure 3 *Inline of PSDM results at injection point. (Left) Based on Phase 1 velocity model and, (Right) Phase 2 velocity model. The arrows mark image improvements, the white lines mark the upward shift.*

which is also clearly visible as a small round structure with a diameter of ca 190m in a horizontal slice (Figure 2, right image). The location of this anomaly coincides with the main chimney reported e.g. by Chadwick et al (2005). The minimum velocity in the plume was found in the largest layer with a value of ca 1400 m/s (before anisotropy scaling). The injection point (well 15/9-A16) is now located correctly at the edge of the deepest low-velocity anomaly (Figure 2, middle image).

In the final PSDM image, the depth of the Base Utsira horizon below the plume has moves upwards by ca 25m, the continuity of the reflector improves, and the residual moveout (RMO) in the common image gathers (CIG) is reduced compared to the Phase 1 PSDM (see Figure 4, left and right image). However, the final image still shows a remaining pull-down compared to images from the 1994 acquisition and the CIGs exhibit remaining RMO. This indicates that the velocities in the plume are still too high.

Conclusion

New 3D high frequency FWI reveals more details in the CO_2 plume at Sleipner compared to previous FWI results. We can now identify at least seven layers with thicknesses down to 15m or smaller, compared to four layers after Phase 1. As importantly, the main chimney is visible in the velocity model and the location of the injection point from well information is now consistent with our model.

The image below the plume improves, even though the velocity in the plume is still too high. We also found that the 1D initial model requires an explicit background correction to reduce imaging errors and to improve the accuracy of the estimated velocity.

As an overall conclusion, the results are promising enough to further investigate the use of 4D FWI for CO_2 storage monitoring in general, and to check in more detail if the results can be used to further estimate properties of the multi-layer CO_2 plume.

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