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Forensic Mapping Of Spatial Velocity Heterogeneity In A CO2 Layer At Sleipner Using Time-Lapse 3D Seismic Monitoring

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Summary

The Sleipner injection operation has stored over 17 Mt of CO2. Time-lapse seismic monitoring has provided high resolution images of CO2 plume development, constraining and verifying numerical flow simulations. Seismic velocity is a key diagnostic parameter for CO2 layer properties and we adopt a forensic interpretative approach to determine velocity variation in the topmost layer of the plume. The 2010 seismic dataset enables, for the first time, temporal thicknesses of the layer to be determined, taking into account interference-induced time-shifts. Combining these with CO2 layer thicknesses determined from structural analysis of the topseal topography allows layer velocity to be mapped. A marked spatial variation in velocity is evident across the layer with higher velocities (1630±103 ms-1) in the central part of the layer contrasting with lower values (~1370± 122 ms-1) to the north. Recent published work has identified a north-trending channel in the topmost Utsira sand unit, which greatly improves history-matching of the topmost CO2 layer with numerical flow simulations. This channel correlates almost exactly with the low velocity area mapped from the seismic, the higher velocity area corresponding to less permeable overbank deposits. The seismic therefore provides key corroborative evidence of permeability heterogeneity within the reservoir sand.

measured at each seismic trace and corrected with the functions developed in the synthetic study to obtain true values of these parameters ΔT_T and ΔE_T.

Figure 3 *Reflections from the top and base of a CO_2 layer and construction of the CWC. a) Synthetic seismic from the ridge model. b) Observed seismic section (near-offset 2010 data) through the topmost CO_2 layer in the northern plume. c) Observed seismic section (near-offset 2010 data) across the central plume. d) Reflectivity map of the topmost layer with location of the two sections*

Layer velocity was calculated from Equation 2 with an overburden velocity of 2150 ms^{-1} (based on well logs and seismic velocity analysis). Analysis was restricted to those parts of the layer above the tuning thickness, giving a total of 2767 traces. Velocities range from around 1200 ms^{-1} to 1800 ms^{-1} (Figure 4a), but with a systematic spatial variation that allows us to define a Northern Area with slow layer velocities and a Central Area with much faster velocities (Figure 4b). Histograms of the Northern and Central areas show normal distributions with mean/median velocity values of around 1372 and 1632 ms^{-1} respectively.

Figure 4 *Velocities for the topmost CO_2 layer. a) Extracted velocities. b) Demarcation into Northern (low velocity) and Central(high velocity) areas. c) Velocity histograms for Northern and Central areas. Polygon in (a) and (b) denotes the CWC limit of the topmost layer in 2010.*

Absolute velocity values scale with the overburden velocity and carry similar uncertainty. Local shallower overburden velocity changes would distort imaging of the topseal, but systematic examination of overburden reflectivity reveals nothing that corresponds to the observed spatial velocity change; which is therefore deemed to be robust.

Discussion and Conclusions

Rock physics using the range of properties observed from Utsira Sand well logs indicates that the velocities of CO_2 layers could range from <1400 to >1500 ms^{-1} for high CO_2 saturations, with higher velocities at intermediate CO_2 saturations. This is supported by recent experimental data and calibrated rock physics from the Utsira core (Falcon-Suarez *et al*. 2018).

Numerical flow modelling of the topmost layer (e.g. Zhu *et al*. 2015) has shown that replicating its rapid northward flow (Figure 3d) with homogeneous reservoir sand properties is very challenging. But recent publications (Williams & Chadwick 2017; Cowton *et al*. 2018) have presented compelling evidence from the baseline seismic data of a north-south trending depositional channel. Including this as a high permeability feature in the flow models greatly improves the ease of obtaining a good history-match. Remarkably, the high permeability channel corresponds almost exactly to the low seismic velocities mapped in the Northern Area. Higher layer velocities in the Central Area would therefore correspond to more argillaceous, less permeable overbank deposits, and possibly associated also with lower CO_2 saturations.

Our results are consistent with rock physics, new experimental data and recent numerical flow simulations and demonstrate for the first time the identification and mapping of important velocity heterogeneity in the Utsira Sand at Sleipner.

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