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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.

Introduction

CO_2 separated from natural gas produced at the Sleipner and Gudrun gas fields is being injected into the Utsira Sand, a regional saline aquifer. The aquifer is in excess of 200 m thick at Sleipner and comprises mostly clean unconsolidated sand of high porosity and permeability. The CO_2 is injected in a dense phase via a deviated well at a depth of 1012 m below sea level, some 200 m beneath the reservoir top. Injection commenced in 1996 with around 17 million tons of CO_2 stored by the end of 2017. A time-lapse seismic monitoring programme has been deployed with a baseline 3D survey acquired in 1994 and several repeat surveys thereafter including the 2010 dataset utilised here.

A key requirement of the monitoring programme is to verify or constrain predictive flow simulations of plume development to demonstrate understanding of reservoir processes and provide the basis for predicting future plume behaviour. Seismic velocity is a key diagnostic for determining CO_2 layer properties and can be estimated from rock physics or, ideally, extracted directly from the seismic data. A number of inversion-based approaches have been deployed at Sleipner including pre- and post-stack stratigraphic inversions and full wave-form inversion, but parameter uncertainty, data limitations and other technical issues have so far limited the precision of these approaches in extracting velocity from a single thin CO_2 layer. Here we adopt a forensic interpretative analysis to determine and map seismic velocity variation in the topmost CO_2 layer at Sleipner. Depositional channels commonly define major permeability fairways in reservoir sands and a key objective is to investigate whether the observed seismic velocity variation can provide evidence for the presence of channeling and lateral permeability variation.

Seismic Data from the 2010 seismic survey

The repeat 3D survey at Sleipner acquired in 2010 had a novel streamer configuration providing improved frequency content (Furre *et al*. 2015).

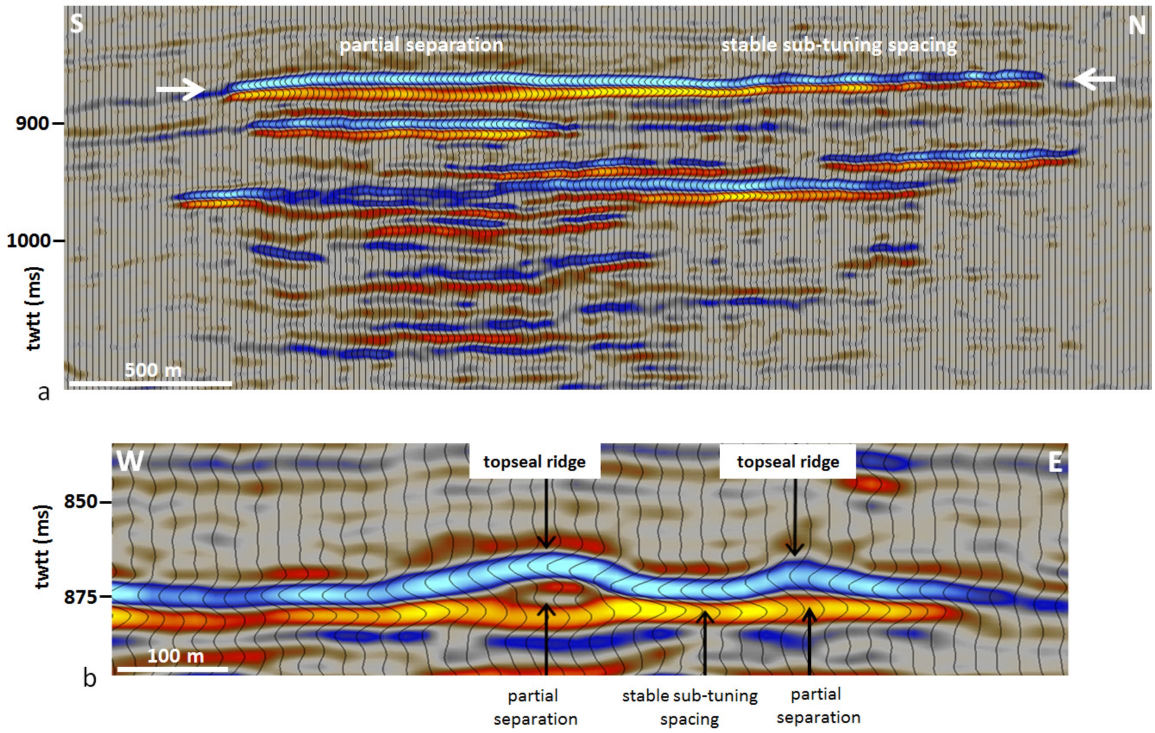

Figure 1 *a) North-south seismic line (full-offsets data) through the 2010 CO_2 plume with topmost layer reflections (arrowed) showing partial separation in southern part. b) West-east seismic line (near-offsets data) showing topmost CO_2 layer with top and base reflections showing partial separation beneath topseal ridges and sub-tuning spacing elsewhere.*

Images of the topmost CO_2 layer reflection on this data clearly show the transition from a sub-tuning wavelet near the layer edges to partially separated reflections in the layer centre (Figure 1a), shown even more strikingly on a near-offset west-east section through north-trending ridges in the topseal (Figure 1b), with partial separation of the top and base layer reflections beneath the ridges and stable sub-tuning spacing elsewhere.

Synthetic seismic modelling and velocity determination methodology

Determining the velocity of the CO_2-filled layer depends on the fact that absolute thickness (in depth) of the CO_2 ponded beneath the overburden relief can be obtained by a simple construction relating the CO_2 – water contact (CWC) to the topographical relief of the reservoir top. Synthetic seismic data were generated for a 3D model of a topseal ridge 10 m high and partially-filled with CO_2 using a wavelet extracted from the 2010 near-offsets dataset (Figure 2). This shows how the CWC, defined explicitly in the model, can be exactly reproduced by fitting a flat horizontal surface through the elevations of the CO_2 reflectivity limits. We can define two parameters: the temporal elevation of the top of the CO_2 layer above the CO_2 - water contact (ΔE_T) and the temporal spacing of the layer (ΔT_T). Measuring from the actual seismic picks however gives ΔE_{OBS} and ΔT_{OBS} which are affected by small time-shifts related to thin layer interference (Furre *et al*. 2015). Time-shift corrections, developed from the model, were applied to obtain ΔE_T and ΔT_T.

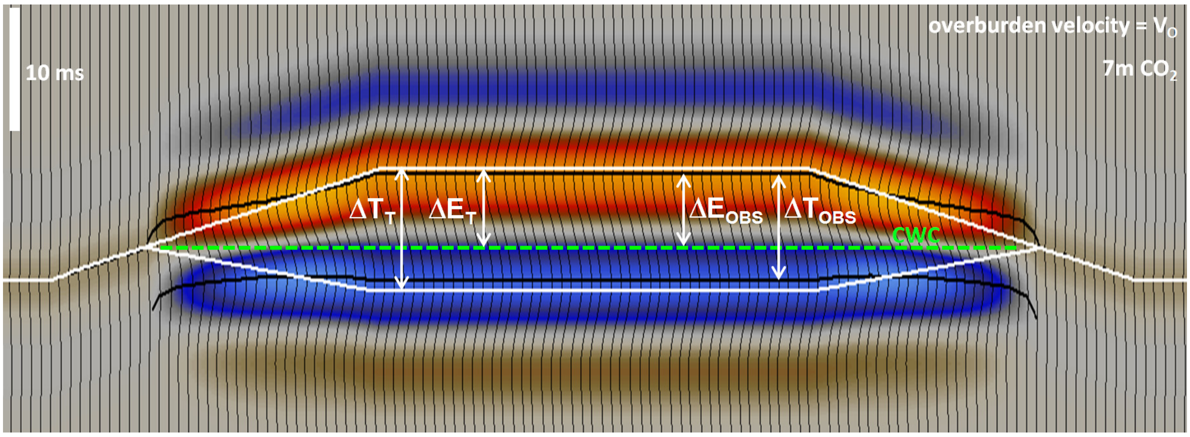

Figure 2 *Synthetic seismic section through the ridge model where the CO_2 layer is 7m thick. White lines show the true top and base of the CO_2 in the model. Black lines show the picked top and base of the CO_2 as imaged by the seismic. Dashed green line shows the actual position of the flat CO_2 – water contact.*

It follows that:

Absolute thickness of CO_2 layer $= \Delta E_T * V_O /2$ *Equation 1*

CO_2 layer velocity V_L = *Absolute thickness of CO_2 layer* $/ (\Delta T_T/2)$

$V_L = V_O * \Delta E_T / \Delta T_T$ *Equation 2*

The CO_2 layer velocity was set at 1400 ms^{-1} in the model with an overburden velocity of 2150 ms^{-1}. Extracting layer velocity from the synthetic seismic picks, using Equation 2 and applying the time-shift corrections, gave a normal distribution of layer velocity with mean and median values of 1399 ms^{-1} and a standard deviation of ±12ms; the statistical scatter due to discretisation and sampling effects in the model and 'jitter' on the seismic picks.

Velocity determination in the topmost CO_2 layer

The methodology was then applied to the topmost CO_2 layer on the real data, by identifying the CWC from the reflection outer limits and constructing a planar CWC surface between them. Analysis of the CWC was restricted to the central part of the plume where clear edge cut-offs and well defined topseal topography allowed it to be constructed with a high degree of confidence. ΔE_{TOBS} and ΔT_{OBS} were 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.

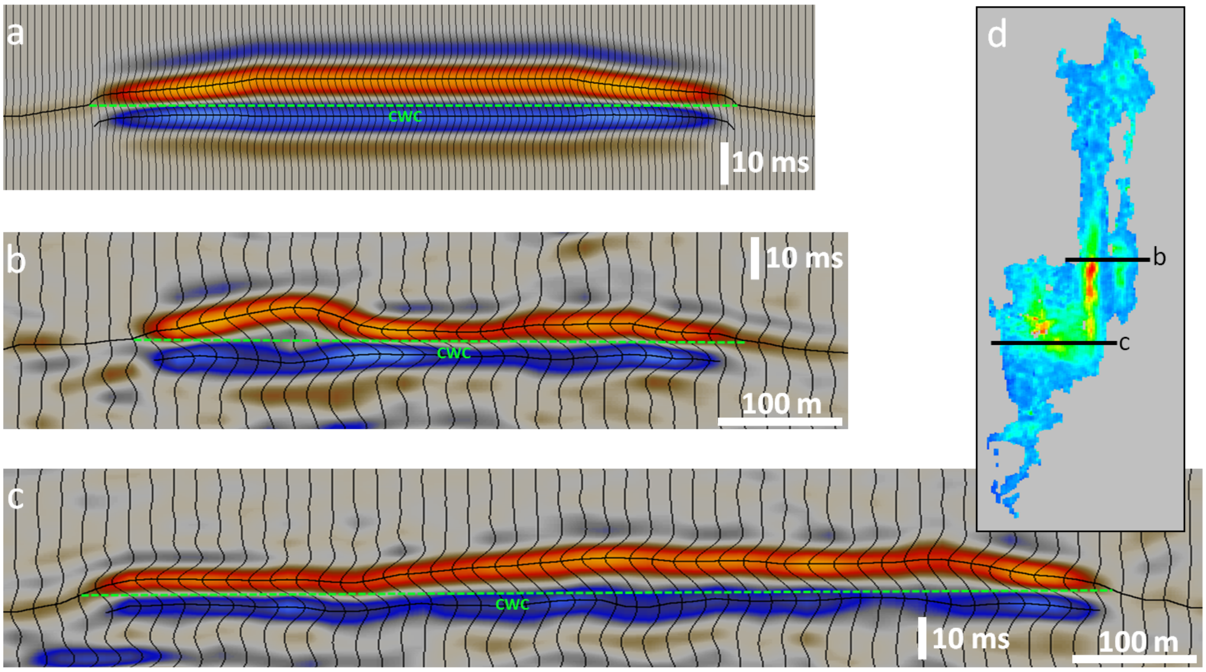

Figure 3 *Reflections from the top and base of a CO_2 layer and construction of the CWC. a) Synthetic seismic from the ridge model. b) Observed seismic section (near-offset 2010 data) through the topmost CO_2 layer in the northern plume. c) Observed seismic section (near-offset 2010 data) across the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

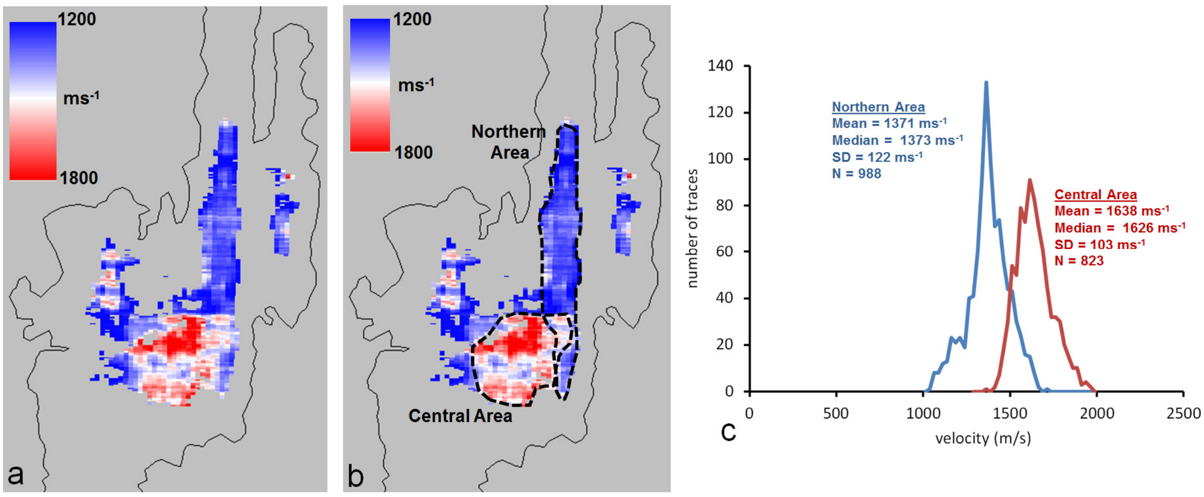

Figure 4 *Velocities for the topmost CO_2 layer. a) Extracted velocities. b) Demarcation into Northern (low velocity) and Central(high velocity) areas. c) Velocity histograms for Northern and Central areas. Polygon in (a) and (b) denotes the CWC limit of the topmost layer in 2010.*

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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