High-resolution imaging and characterization of a CO₂ layer at the Sleipner CO₂ storage operation, North Sea using time-lapse seismics

R.A. Chadwick¹, G.A. Williams¹ and J.C. White¹ explore the extent to which recent time-lapse seismic data, together with a forensic interpretative approach, can provide new quantitative constraints on layer properties.

Large-scale underground storage of industrially produced carbon dioxide is the most effective way of keeping cumulative man-made emissions of greenhouse gases within safe limits (IPCC, 2005). The CO₂ injection operation at Sleipner, in the central North Sea between the UK and Norway, commenced in 1996 and is the world’s longest-running industrial-scale storage project. It is also the first example of underground CO₂ storage arising as a direct response to environmental legislation (Baklid et al., 1996).

CO₂ separated from natural gas produced at the Sleipner field is being injected into the Utsira Sand, a regional saline aquifer of late Cenozoic age, in excess of 200 m thick in the Sleipner area (Figure 1a). The aquifer comprises mostly clean unconsolidated sand of high porosity (> 0.3) and high permeability (> 1 Darcy). A number of thin intra-reservoir mudstones, typically 1-2 m thick, are evident from geophysical logs acquired in wells around Sleipner (Figure 1b).

The CO₂ is injected in a dense phase via a deviated well at a depth of 1012 m below sea level, approximately 200 m beneath the top of the reservoir. Injection commenced in 1996 at a roughly constant rate, with around 16 million tonnes of CO₂ stored by 2015. A comprehensive deep-focused monitoring programme has been deployed of which time-lapse seismic has proven to be the key tool (Arts et al., 2008). A baseline 3D survey was acquired in 1994, with repeat surveys in 1999, 2001, 2004, 2006, 2008, 2010 and 2012.

The plume is imaged on the seismic data as a tiered structure some 200 m high comprising a number of bright sub-horizontal reflections (Figure 2a). These are interpreted as reflections from thin layers of CO₂ trapped beneath the intra-reservoir mudstones which are partially but not wholly sealing. The reflective layering had formed by 1999 with each individual reflection traceable on all of the subsequent surveys. As a general rule the middle and upper reflections in the plume have increased in amplitude and lateral extent on successive time-lapse surveys, whereas the lower layers have ceased growing, in some cases shrinking and dimming.

A key objective of the monitoring at Sleipner is to demonstrate that geological storage of CO₂ is a safe and viable technology. One aspect of this is to quantitatively verify or constrain predictive flow simulations of plume development. However, because the injection well is near-horizontal, no wellbore penetrates either the CO₂ plume or the exact stratigraphy that the plume now occupies, and quantitative analysis is challenging.

Crucial to understanding development of the CO₂ layers are their geophysical and physical properties. Seismic velocities can be obtained from rock physics, but in the absence of any independent constraints (no wellbore penetrates any of the CO₂ layers), uncertainties are significant, particularly with regard to CO₂ properties. Seismic inversion (e.g. Delépine et al., 2011) can provide estimates of layer velocity, but because of resolution limitations inverted layer thicknesses and velocity values are generally inaccurate. This
Development and properties of the topmost CO₂ layer in the plume

With time it is likely that most of the injected CO₂ will end up trapped beneath the undulating reservoir topseal where it has the potential to migrate laterally over significant distances (Chadwick et al., 2008). In terms of medium to long-term storage site performance therefore, understanding the topmost CO₂ layer of the plume is a key objective.

Reflection amplitude changes at the top of the Utsira Sand illustrate the development of the topmost layer through time (Figure 2b). CO₂ reached the reservoir top in 1999 as two small accumulations just prior to the first time-lapse survey. By 2001 these had coalesced into a single accumulation which continued to spread thereafter. A north-trending linear prolongation of the layer is particularly prominent and corresponds to CO₂ migrating northwards along a linear ridge at the reservoir top (Figure 3a).

It is clear that the topmost layer is spreading by a dominantly buoyancy-driven fill-spill process, with CO₂ supplied from the deeper plume migrating laterally beneath the top reservoir relief (Figure 3b). A number of studies (e.g. Chadwick and Noy, 2010; Cavanagh, 2013; Zhu et al., 2015) have obtained geometric matches of the observed monitoring data with numerical flow models and all agree that the CO₂ is migrating beneath topographic features in the reservoir topseal via a buoyancy-driven fill-and-spill process. However, uncertainties remain, particularly regarding the rate at which the CO₂ attains its buoyancy-stable configuration, and the key controls on CO₂ mobility: temperature, reservoir properties and whether flow follows Darcy’s Law or is dominated by capillary processes (Cavanagh, 2013).
Topseal topography
A robust understanding of layer morphology requires an accurate knowledge of the small topographic depth changes around the structural features that the topmost layer of CO₂ occupies. Topography of the Utsira topseal, mapped in travel-time from the 1994 baseline survey (Figure 3a), shows a small domal structure above the injection point which prolongates to the north via a prominent north-trending linear ridge; this in turn widens northwards into another domal structure. A smaller, parallel ridge lies to the east. The overall positive relief of the domes and ridges compared to the surrounds is typically up to around 20 milliseconds (ms).

Overburden velocity information is required to obtain a depth surface. A number of wells in the vicinity have velocity data of which the closest are Norwegian wells 15/09-13 and 15/09-16, some 2 and 4 km to the WSW of the central part of the plume respectively. In addition, full spatial overburden velocity coverage is provided by stacking velocities from the 3D seismic processing which was carried out with great care including 4th order polynomial fitting for the move-out correction.

Both wellbore and seismic data show a systematic increase in overburden velocity with travel-time, but no systematic spatial variation in velocity was evident in the seismic stacking velocities. In addition wellbore spacings are too large to map variation on the relevant spatial scale (Chadwick and Noy, 2010), so a laterally uniform but time-variant overburden velocity was assumed. The computational equivalent of depth-converting with a laterally uniform time-variant average velocity is to place the travel-time topography within a layer of laterally uniform constant velocity corresponding to the lowest interval of the time-variant velocity trend. This is a convenient approach to adopt because it allows analysis to be carried out in the travel-time domain with a single-velocity depth conversion afterwards. In practice we calculated interval velocities for the lowest few tens of metres of the overburden (Table 1). This lies within the laterally rather uniform ‘Lower Seal’ (Chadwick et al., 2004) whose interval velocity might be expected to be similarly uniform. Calculated well log values are in the range 2133 to 2159 ms⁻¹. Dix interval velocities derived from the stacking velocities show a smooth, somewhat skewed, distribution with 90% of values lying in the range 2075 to 2225 ms⁻¹. This variation comprises small but real geological variations in velocity together with random data noise. Taking all this information together, a velocity value of 2150 ± 46 ms⁻¹ was estimated for the basal overburden interval.

CO₂ layer thickness
The thickness of the CO₂ layer ponded beneath the overburden relief can be obtained by topographical

<table>
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<tr>
<th>Data source</th>
<th>Interval velocity</th>
<th>Uncertainty</th>
<th>Comments</th>
</tr>
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<tbody>
<tr>
<td>Nearby well logs average</td>
<td>2150 ms⁻¹</td>
<td></td>
<td>Zweigel et al., 2004</td>
</tr>
<tr>
<td>Well 15/09-13</td>
<td>2159 ms⁻¹</td>
<td></td>
<td>Basal 35 m of overburden</td>
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<tr>
<td>Well 15/09-16</td>
<td>2133 ms⁻¹</td>
<td></td>
<td>Basal 30 m of overburden</td>
</tr>
<tr>
<td>Dix interval velocity (seismic)</td>
<td>2137 ms⁻¹</td>
<td>± 46 ms⁻¹ (SD)</td>
<td>Basal –50 m of overburden over plume</td>
</tr>
</tbody>
</table>

Table 1 Interval velocities for the lower part of the overburden.
It is notable that the CO₂ layer thickness increases up to more than 10 m in its central parts, with local peaks approaching 15 m.
CO₂ Layer properties
The seismic properties of the CO₂ layer are not understood in detail. The temperature at the top of the reservoir is about 29°C (Alnes et al., 2011) and the pressure is believed to be close to hydrostatic (Chadwick et al., 2012). There are a number of equations-of-state for CO₂ and all agree that at these P,T conditions CO₂ is in a dense phase with a density of around 50-70% that of water, but a compressibility less than 5% that of water, which results in its low seismic velocity. The properties of water-saturated Utsira Sand in the vicinity of Sleipner are known from well logs. Rock physics calculations based on Gassmann fluid substitution suggest lowering of seismic velocity from around 2050 m/s in the water-saturated sand to around 1430 m/s in the fully-CO₂ saturated sand, the velocity-saturation relationship depending on mixing scales (Figure 5).

Nevertheless, the actual properties of the layer remain elusive. Rock properties around the CO₂ plume itself have not been measured and, in addition, Alnes et al. (2011) indicate that, due to adiabatic compression in the wellbore, the CO₂ is a few degrees warmer than the reservoir itself, particularly in the axial parts of the plume. The extent to which this thermal anomaly spreads laterally across the topmost layer is the subject of ongoing study. Because of these uncertainties, direct measurement of the reflective layer is essential to properly constrain CO₂ seismic properties and from these its crucial flow properties (notably viscosity and density).

Seismic imaging of the topmost layer
Previous work on seismic amplitudes and tuning effects
It is clear that the seismic reflectivity of the layer varies markedly and rather systematically (Figure 2b). It was quickly established (Arts et al., 2004; Chadwick et al., 2004) that, at least in its early stages of development, the CO₂ plume was characterized by layers of CO₂ whose thickness was less than one quarter the dominant seismic wavelength (λ/4). Reflections from such ‘thin’ layers are formed by interference between reflections from the top and base of the layer and are termed ‘tuning wavelets’.

Amplitudes of the reflection ‘trough’ from the top of the layer and the reflection ‘peak’ from the base of the layer increase systematically as layer thickness increases towards λ/4, which is termed the tuning thickness (Figure 6a). Above this, amplitudes decrease somewhat towards the fully separated situation where they most accurately reflect the impedance contrasts at the top and base of the CO₂ saturated layer.

The tuning wavelet is characterized by constant temporal separation between the reflection ‘trough’ from the layer top and the reflection ‘peak’ from the layer base (Figure 6b). Above the tuning thickness temporal separation starts to increase gradually through a ‘partially separated’ stage until a point is reached where interference effects become minimal and the temporal separation of the top and base reflections more-or-less reflects the true thickness of the layer and its seismic velocity. The top and base reflections can then be said to be ‘fully separated’. A synthetic wedge model using the Sleipner seismic wavelet and a layer velocity of 1428 m/s illustrates this (Figure 6c). The theoretical temporal separation, defined as twice the layer thickness divided by the layer velocity, is only matched by the modelled separation for layer thicknesses greater than about 12 m. Above the tuning thickness, the ratio of the modelled temporal separation to the theoretical separation ranges from about 1.1 to 0.9, converging on 1.0 at higher layer thicknesses (Figure 6d).

Imaging the topmost layer in 2010
The sixth repeat 3D survey at Sleipner was acquired in 2010 and had a novel streamer configuration utilizing dual sensor streamer technology which combines hydrophone recording
with vertical particle movement recording to allow separation of the upgoing and downgoing wavefields. This helps to eliminate the receiver ghost and gives broader frequency content than hydrophone data alone (Furre and Eiken, 2014). Thus the conventional time-lapse data at Sleipner have typically had a frequency spectrum in the range 8 to 80 Hz (-20 dB), whereas the 2010 data span the range 8 to 110 Hz (-20 dB).

Images of the topmost layer reflection on the 2010 dataset (Figure 7) clearly show the transition from a tuning wavelet near the layer edges to partially separated reflections in the

Figure 8 a) Map of measured temporal spacing of the topmost CO₂ layer. b) Two-way travel-time map of the Utsira Sand topseal topography showing the domal structures and ridges (orange/red colours). Faint polygon shows the outline of the topmost CO₂ layer in 2010. Bold rectangle denotes area included in time-shift analysis. North-trending ridges A and B also shown.

Figure 9 Two east-west seismic lines through the main ridge (A) and a smaller ridge (B) to the east. Top and base reflections show partial separation beneath the ridges with varying amounts of velocity pushdown beneath the ridges ranging from positive (+ve) through to negative (-ve).
layer centre (Figure 7b). This transition is particularly clearly displayed by mapping the temporal spacing on the top and base reflections (Figure 8a). Temporal spacings on the tuning wavelet, at around 6-7 ms, are strikingly uniform, compared with the increased temporal spacings in the central parts of the layer. It is also clear how the increased temporal spacings correspond very closely with topographic highs in the topseal relief.

In detail, the layer reflectivity shows some intriguing features, particularly evident in the vicinity of the two north-trending linear ridges A and B (Figure 9). The top layer reflection follows the topseal relief and shows the two ridges clearly. Bearing in mind that the base of the CO₂ layer (the CWC) is assumed to be roughly flat in depth (Figure 4a), the base reflection geometry is more complex. There are essentially three configurations beneath the ridges: 1) flat base reflection in tWT, 2) base reflection showing positive velocity pushdown and 3) base reflection which follows the top reflection trend, with essentially ‘negative’ pushdown.

In qualitative terms this can be explained in terms of the CO₂ layer thickness beneath the ridges. Thus, a very thin layer might well be in the tuning wavelet range beneath the ridge flank and also beneath the ridge crest. The constant temporal separation therefore results in an apparent ‘pull-up’ under the ridge crest (Figure 9b). Reflections from a thicker CO₂ layer might be tuned beneath the flanks but will enter...
the partial separation state beneath the ridge crest allowing for a detectable velocity pushdown to develop (Figure 9a).

**Topmost layer properties**
Quantitative analysis of the interplay between ridge elevation, layer thickness and layer properties in terms of reflection time-shifts is complex and is the subject of ongoing studies involving detailed seismic synthetic forward-modelling. Here we present preliminary results from some simple relationships.

**Layer velocity from time-shifts**
A second approach is to look at the very small time-shifts of the top and base layer reflections which determine the relationship between top layer topography and velocity pushdown (Figure 11a).

With a perfectly resolved seismic image (for a seismic ‘spike’ with no interference between the top and base layer wavelets) there is a simple relationship between time-shifts due to topographic variation at the top layer reflection and time-shifts due to velocity pushdown at the base layer reflection:

$$\Delta T_p = \Delta T_E \left(\frac{V_o}{V_R} - 1\right)$$  \hspace{1cm} (1)

Where:

- $\Delta T_p$ = time-shift at top layer reflection
- $\Delta T_E$ = time-shift at base layer reflection
- $V_o$ = overburden velocity
- $V_R$ = CO₂ layer velocity

Rearranging Equation 1 gives an expression for $V_R$ as a function of the overburden velocity and the time-shifts at the top and base of the CO₂ layer:

$$V_R = V_o \left(\frac{\Delta T_p}{\Delta T_E} + 1\right)$$  \hspace{1cm} (2)

$\Delta T_E$ and $\Delta T_p$ can readily be measured from seismic data (Figure 11b) and so $V_R$ can be calculated if $V_o$ is known. $\Delta T_E$ and corresponding values of $\Delta T_p$ were measured on multiple seismic traces on the flanks and crest of ridge A (Figure 8b) and from these $V_R$ calculated (Figure 12). In practical terms, measured values on the ridge flanks are affected by seismic noise and also by tuning effects of various kinds (Furre and Eiken, 2014), both of which affect the measured time-shifts. Errors are proportionately higher for small values $\Delta T_E$ and $\Delta T_p$ so to minimize these effects we restricted analysis to seismic traces in the vicinity of the ridge crest where $\Delta T_E$ values are greater than 2 ms.

The layer velocities, calculated trace-by-trace, show roughly symmetrical distributions (Figure 12). The velocity range is largest for the 209 traces where $\Delta T_E$ is >2 ms (Figure 12a). Deviations from the mean are mostly associated
with measurement and imaging errors of various types and so the distributions become increasingly tight as those seismic traces farther from the ridge crest (with small $\Delta T_E$ and $\Delta T_p$ values) are thresholded out (Figures 12 b, c).

The median values of around 1400 ms$^{-1}$ are consistent with the velocities obtained from the structural analysis (above). Both sets of velocity determinations are consistent with the rock physics (Figure 5), assuming that the layer is characterized by high fluid saturations and/or uniform fluid mixing. The latter are consistent with our knowledge of capillary properties in the reservoir. The analysis also supports earlier quantitative estimates of plume CO$_2$ (e.g. Chadwick et al., 2005) which depended solely on rock physics.

It is important to note that Equations 1 and 2 are exact only for a hypothetical normal incidence spike wavelet with no top/base reflection interference. We minimized interference effects by analysing only traces where ridge elevations (and layer temporal thicknesses) were relatively large. Nonetheless, tuning effects are not negligible (Furre and Eiken, 2014). A much more detailed study, involving full forward synthetic seismic modelling using a comprehensive range of ridge elevation, layer thickness and layer velocity is currently underway to fully tease out these subtle effects and improve velocity determination still further.

Conclusions

Detailed interpretation of the 2010 time-lapse seismic survey at Sleipner, along with judicious application of geological constraints, has enabled assessment of the seismic properties of the topmost layer in the CO$_2$ plume. Layer velocity has been estimated by two methods. Structural analysis of the top layer topography and the CO$_2$ – water contact combined with observed temporal layer thicknesses – gives velocities in the range 1350 to 1400 ms$^{-1}$. Measurement of very small time-shifts of the layer top and base reflections gives velocities in the range 1390 to 1430 ms$^{-1}$. In both cases uncertainty (standard deviation) is in the order of ± 60 to 140 ms$^{-1}$. These figures are consistent with values derived independently from rock physics. It is stressed however that the analysis is preliminary, as the effects of wavelet interference have not been fully accounted for. Further work is ongoing in this respect.

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