Quantitative analysis of time-lapse seismic monitoring at the Sleipner CO_2 storage operation

ANDY CHADWICK, VINCENT CLOCHARD, NICOLAS DELEPINE,KARINE LABAT, SUSAN STURTON, MAIKE-L BUDDENSIEK, MENNO DILLEN, MICHAEL NICKEL, ANNE LOUISE LIMA, GARETH WILLIAMS, FILIP NEELE, ROB ARTS and GIULIANA ROSSI

The CO_2 storage operation at Sleipner in the Norwegian North Sea provides an excellent demonstration of the application of time-lapse surface seismic methods to CO_2 plume monitoring under favourable conditions. Injection commenced at Sleipner in 1996 with CO_2 separated from natural gas being injected into the Utsira Sand, a major saline aquifer of late Cenozoic age. CO_2 injection is via a near-horizontal well, at a depth of about 1012 m bsl, some 200 m below the reservoir top, at a rate approaching 1 million tonnes (Mt) per year, with more than 11 Mt currently stored.

A comprehensive time-lapse surface seismic programme has been carried out, with 3D surveys in 1994, 1999, 2001, 2002, 2004, 2006 and 2008. Key aims of the seismic monitoring are to track plume migration, demonstrate containment within the storage reservoir and provide quantitative information as a means to better understand detailed flow processes controlling development of the plume in the reservoir.

The CO_2 plume is imaged as a number of bright sub-horizontal reflections within the reservoir, growing with time (Figure 1). The reflections mostly comprise tuned wavelets arising from thin (mostly < 8 m thick) layers of CO_2 trapped beneath very thin intra-reservoir mudstones and the reservoir caprock. The plume is roughly 200 m high and elliptical in plan, with a major axis increasing to over 3000 m by 2008. As well as its prominent reflectivity, the plume also produces a large velocity pushdown caused by the seismic waves travelling more slowly through CO_2-saturated rock than through the virgin aquifer.

This paper summarises some of the quantitative methods that have been applied to the Sleipner seismic datasets.

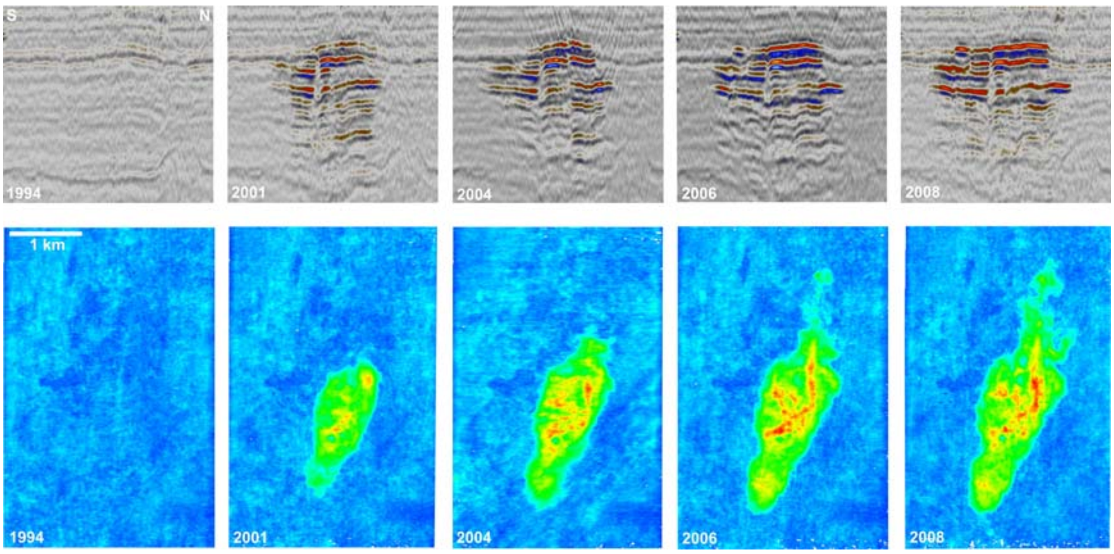

__Figure 1.__ Time-lapse seismic images of the Sleipner CO_2 plume. North – south inline through the plume (top); plan view of total reflection amplitude in the plume (bottom).

Quantitative interpretation. Quantitative verification of the whole plume is not a regulatory requirement for CO_2 storage, but is an interesting technical challenge nonetheless. Early interpretive work on reflection amplitudes and velocity pushdown derived a 3D saturation model for the 1999 dataset which contained around 85% of the known injected CO_2 whilst maintaining a satisfactory match with the seismic data (Chadwick et al., 2005). Flow simulations suggest around 10 % of the free CO_2 would have dissolved into the aqueous phase (thereby becoming seismically invisible), so this may be considered a satisfactory result. The more recent Sleipner datasets are becoming more difficult to quantify in their entirety, as with time, reflectivity in the deeper plume is fading and velocity pushdown is becoming more difficult to map (Figure 1). This may signify real and significant changes in CO_2 distribution in the deeper part of the plume or, alternatively, may arise from seismic imaging effects arising from generally increasing CO_2 saturations within the plume envelope.

A general tendency of CO_2 to progressively accumulate in the upper part of the reservoir is evident (Figure 1). The topmost layer of the plume is particularly clearly imaged, mappable via its strong reflectivity (Figure 2 left). CO_2 first reached the reservoir top in 1999, growing to an accumulation of considerable lateral extent by 2001 and continuing to expand thereafter. Lateral migration was strongly controlled by the top reservoir topography, exemplified by a north-trending linear finger of CO_2 migrating along a narrow sedimentary ridge in the basal topseal surface (Figure 2 centre).

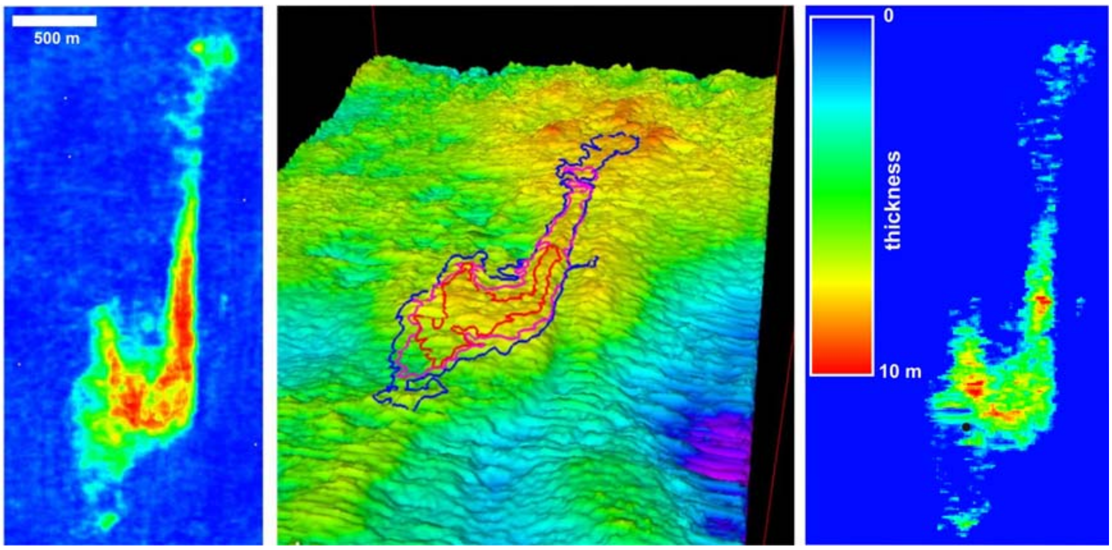

__Figure 2.__ The topmost CO_2 layer in the Sleipner plume. Left: Map of seismic amplitudes in 2006. Centre: 3D view (looking north) of the top Utsira Sand surface (mapped on the baseline 1994 dataset) showing the CO_2 - water contacts in 2001 (red), 2004 (purple and 2006 (blue). Right: Topmost layer thicknesses in 2006, derived from structural analysis.

Earlier quantitative work has utilised the relationship of reflection amplitude to CO_2 layer thickness. An alternative way of estimating the thickness of the topmost CO_2

layer is by topographic analysis of the reservoir top (Figure 2 centre), the outer limit of CO_2 reflectivity at this level corresponding to the CO_2 - water contact (CWC). Assuming the layer to be ponded buoyantly beneath the topseal, the form of the fluid contact at its base was constructed by fitting a smooth subhorizontal surface through the elevations of the CWC (the surface is not perfectly horizontal because it is constructed in two-way time, not depth and also because of significant fluid dynamic effects). The two-way time thickness of the topmost layer was then calculated by subtracting the elevations of the reservoir top from the corresponding elevations of the CWC. These were then converted to depth thicknesses by assuming an appropriate velocity model for the overburden (Figure 2 right). Uncertainty in these structurally-derived thicknesses relate mainly to uncertainties in overburden velocities, but it is also clear that layer reflectivity extends into areas where the structurally-derived layer does not, most notably south of the injection point (Figure 2). This is because the structural analysis does not allow CO_2 to be present wherever the constructed CWC is shallower than the topseal. In reality the CO_2 layer is a dynamic entity with significant horizontal flow and likely supplied from below by a number of feeders, some of which may lie beneath topographically 'overdeepened' areas in the topseal.

The saturation of CO_2 within the topmost layer can be estimated using measured capillary pressures for the Utsira Sand, and from this CO_2 volumes within the layer can be calculated. Based on these volumes, flow simulations of layer growth have been history-matched against the observations and understanding of flow processes within the reservoir has been improved (e.g. Chadwick et al. 2009).

Model-based inversion. Stratigraphic inversion is used to better characterize reservoirs by integrating various kinds of information obtained at different scales, combining geological (e.g. well-log and sedimentological data) and geophysical information (e.g. vertical seismic profiles, picked seismic horizons) in a target-oriented inversion process.

A post-stack stratigraphic inversion of the 1994 and 2006 datasets was used to obtain acoustic (P-wave) impedances for the Sleipner plume (Delépine et al., 2009). Pre-stack inversion allows derivation of a more complete elastic model, parameterized by both P- and S-wave impedances. Elastic properties are important for subsurface characterization as they can be used in favourable cases to determine additional petrophysical properties such as porosity and permeability.

We present here results obtained from a model-based pre-stack inversion applied to the 1994 (baseline) and to the 2006 (after injection of 8.4 Mt of CO_2) time-lapse seismic datasets. The pre-stack data considered in our inversion fall into three angle classes built from partial stacks according to incidence angle: "near" (6° to 16°), "mid" (17° to 27°) and "far" (28° to 38°). The pre-stack inversion methodology comprises three steps:

Well-to-seismic calibration. This step aims to find optimal wavelets which ensure consistency between well log data and surface seismic data through the Aki and Richards approximation. For each vintage three optimal wavelets were derived, one for each angle class, to compensate for issues in pre-processing and to correct for propagation effects in the overburden.

***A priori* model building.** Pre-stack stratigraphic inversion requires an *a priori* multi-parameter elastic model parameterized as P- and S-wave impedances. Interpreted horizons picked from the seismic data were used to define the structural and stratigraphical framework (Figure 3). Within each unit sedimentological constraints were used to compute correlation surfaces. Calibrated elastic impedance and density log information was then integrated into the model by extrapolation along the correlation surfaces.

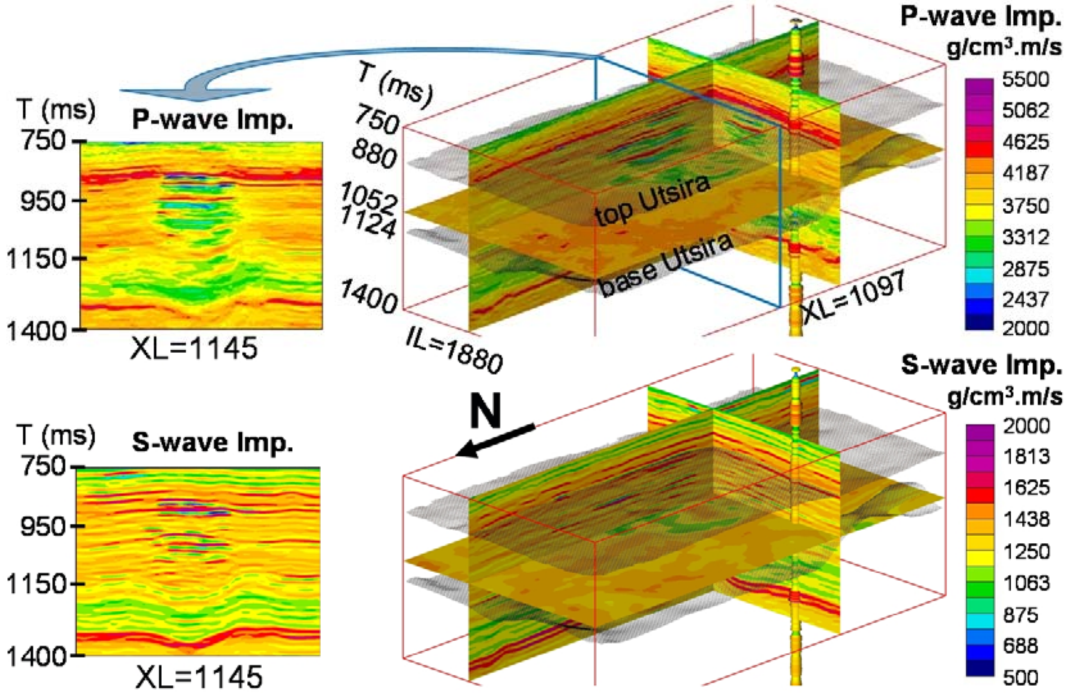

Figure 3. *P-wave and S-wave optimal impedances obtained after pre-stack inversion of the 2006 vintage (crossed planes: XL1097, IL1880 and time slice: t=1052 ms), showing the picked top and base Utsira Sand. The impedance log derived from exploration well 15/9-13 is shown for comparison (right). Vertical distributions of acoustic impedance obtained at a selected crossline XL1145 (left).*

Joint pre-stack stratigraphic inversion of all angle classes. The pre-stack stratigraphic inversion algorithm described by Tonellot et al. (2001) was applied to a 750-1400 ms time window. Strong weighting was given to the *a priori* information, by stipulating high correlation length values, because the geological layers are relatively flat and there is only weak lateral variation of impedance outside of the CO_2 plume. Results after 50 iterations show the optimised 3D distribution of P- and S-wave impedances (Figure 3). Impedances inferred from the nearby well 15/9-13 show good correlation with the cross-section along XL1097. The optimised P- and S-wave impedance model was used to compute synthetic seismic data for each angle class (Figure 4). For the section along inline IL1850, a good fit is observed between real and synthetic data for both the near and far angle classes in terms of amplitude and waveform in the middle of the plot (on both sides of the red line).

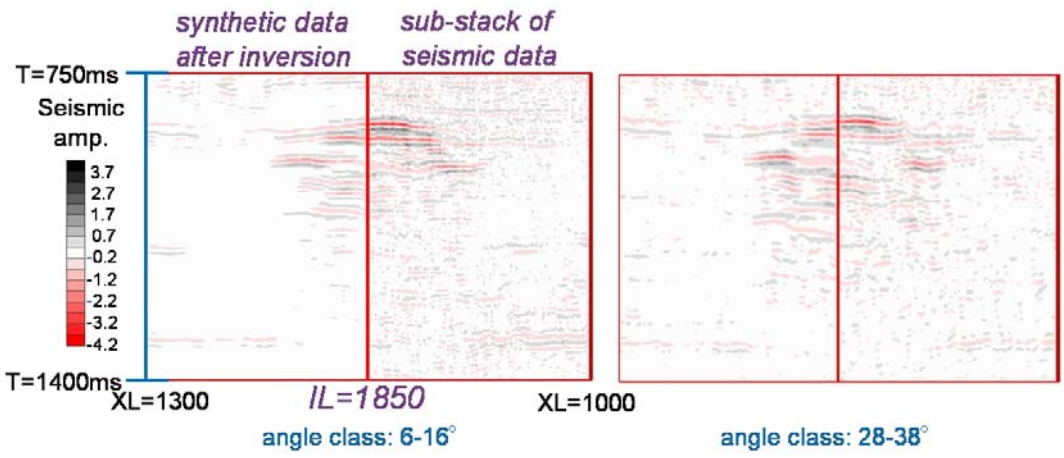

Figure 4. *Comparison between observed and synthetic data computed after pre-stack inversion of the 2006 vintage: vertical slice at inline position IL1850 for the "near" angle and "far" angle partial stacks.*

Discusson of results. Within the impedance cube on XL1145 (Figure 3), the CO_2 plume is seen clearly as a strong reduction in P-wave impedances, locally to less than 2500 $m.s^{-1}.g.cm^{-3}$, compared with around 4000 $m.s^{-1}.g.cm^{-3}$ in the virgin aquifer. Rock physics analysis on an Utsira Sand model containing CO_2 at medium to high saturations gives P-wave impedances similar to those calculated for the upper part of the CO_2 plume (Figure 3). However, determination of unique CO_2 saturations from impedance values remains very challenging.

Well logs reveal several thin mudstones within the Utsira Sand. The thickest of these, located just below the top of the reservoir, has a thickness of 5 m or more and is visible on the impedance displays (Figure 3). The other intra-reservoir mudstones are below seismic resolution, but they can be delineated if the two following conditions are met: they are illuminated by CO_2 trapped beneath them, or their separation in depth is large enough relative to the dominant wavelength of the seismic data. Thus we also observe a mudstone layer at around 940 ms on the P-wave impedance display which overlies a significant accumulation of trapped CO_2.

The time-lapse seismic data show a progressive attenuation of seismic events beneath the CO_2 plume which increases with time (Figure 1). Attenuation of a strong reflection at around 1300 ms was noted by Clochard et al. (2009). This effect is reduced on the P-wave impedances result (Figure 3 left) because the inversion process is a trade-off between the seismic data and *a priori* geological knowledge. Indeed, the inversion of P-wave seismic data alone is unable to fully recover the S-wave impedance, so the process gives more weight to the *a priori* S-wave model resulting in S-wave impedances with very little attenuation.

The pre-stack inversion results were compared to those of post-stack inversion (Clochard et al. 2009). The pre-stack inversion seems better able to characterize some parts of the reservoir, particularly the sand unit between the reservoir top and the uppermost intra-reservoir mudstone. In the 1994 pre-stack inversion, the average seismic bandwidths of the "near", "mid" and "far" angle classes are: 14-64 Hz, 15-61

Hz and 13-56 Hz, respectively at -6 dB. In the post-stack case the average seismic bandwidth is 14-59 Hz. In addition, the pre-stack inversion process combines the long wavelengths of the seismic impedances (derived from well log data and stacking velocities) with seismic data sorted according to angle classes. It thus covers a frequency bandwidth from 0 to 64 Hz, with resolution superior to that obtained by post-stack inversion.

Ancillary quantitative tools. A number of quantitative methods do not in themselves address analysis of the whole plume, but can provide valuable ancillary information in understanding and quantifying CO_2 distributions.

Spectral decomposition. Frequency tuning of the seismic wavelet can be used to extract layer thicknesses from seismic data. To do this for an individual CO_2 layer however, requires a very short analysis window. To this end, spectral decomposition algorithms incorporating the quadratic Wigner-Ville Distribution (WVD) and the Continuous Wavelet Transform (CWT) have been developed. After rigorous testing on synthetic data, the algorithms are being applied to the Sleipner datasets, concentrating on the topmost layer of CO_2. An east-west cross-section shows strong frequency tuning in the tongue of CO_2 trapped beneath the north-south trending ridge in the topseal (Figure 5). The CO_2 layer beneath the axial part of the ridge shows tuning at about 35 Hz, whereas the beneath the flanks it tunes at about 65 Hz and possibly up to 75Hz. These frequencies correspond to temporal layer thickness from about 15 ms beneath the ridge crest to around 6 ms on the flanks. Combining these figures with independent constraints on the true thickness of this layer (see above) suggest layer velocities in the range 1200 to 1500 ms^{-1}, consistent with rock physics estimations. Work is in progress to further quantify CO_2 layer thicknesses and velocities in this layer.

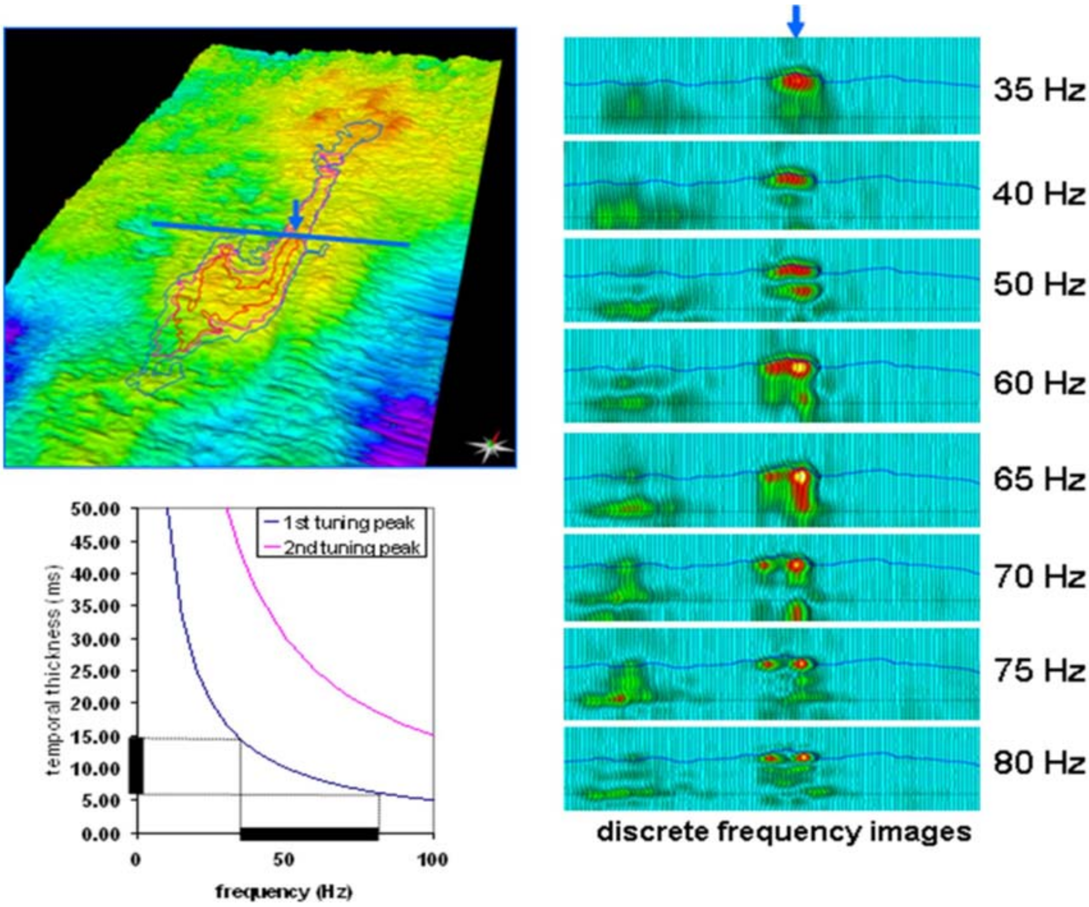

Figure 5. *Frequency tuning on the topmost CO_2 layer in the Sleipner plume.*

AVO analysis. Constrained AVO analysis is being used to estimate the thickness of the CO_2 layers. This is non-trivial because the CO_2 collects in thin layers of variable saturation, beneath mudstone beds that are between one and a few metres thick. Conventional AVO methods, using linear approximations to the Zoeppritz Equation, fail when applied to thin layer reflections due to interference between reflections within the layer. Here, we obtain AVO reference curves $R(\theta)$ by using reflectivity modelling which takes into account these interference effects. Optimal basis functions ($f_1, f_2\ldots$) are obtained from the reference curves using a singular value decomposition, which results in the linear approximation:

$$R(\theta) \approx C_1 f_1(\theta) + C_2 f_2(\theta) + \ldots$$

where C_1 and C_2 are coefficients parameterising the equation (Causse et al., 2007). Cross-plots of these coefficients can potentially be used for classification and determination of layer thickness, as will be shown below, provided different classes of reflector show sufficient separation.

Reflectivity modelling requires knowledge of seismic velocities, densities, and layer thicknesses and the modelled reference curves need to cover the range of variability in the reservoir. The ranges in the properties of the mudstone and brine saturated sand layers were obtained from well logs. Properties with CO_2 present were calculated using an equation-of-state and different rock physics relations for different types of fluid mixing (uniform to patchy). Uncertainties in measurements of pressure and temperature are accounted for by choosing values from a normal distribution.

Saturation profiles for the CO_2 layers, calculated from capillary pressure data, show variable CO_2 saturations with depth. In the reflectivity modelling this is approximated as multiple thin layers, each with a constant saturation.

Figure 6 shows a sample set of reference curves for different CO_2 layer thicknesses. For each assumed CO_2 layer thickness all other parameters are varied randomly within ranges reasonable for Sleipner. As the CO_2 layer thickness increases, the reflection coefficients first become more negative, with a minimum value at a thickness of 7.5 m, similar to the tuning thickness from Chadwick et al. (2005). Then, they become more positive again and therefore overlap with the coefficients of some of the thinner layers.

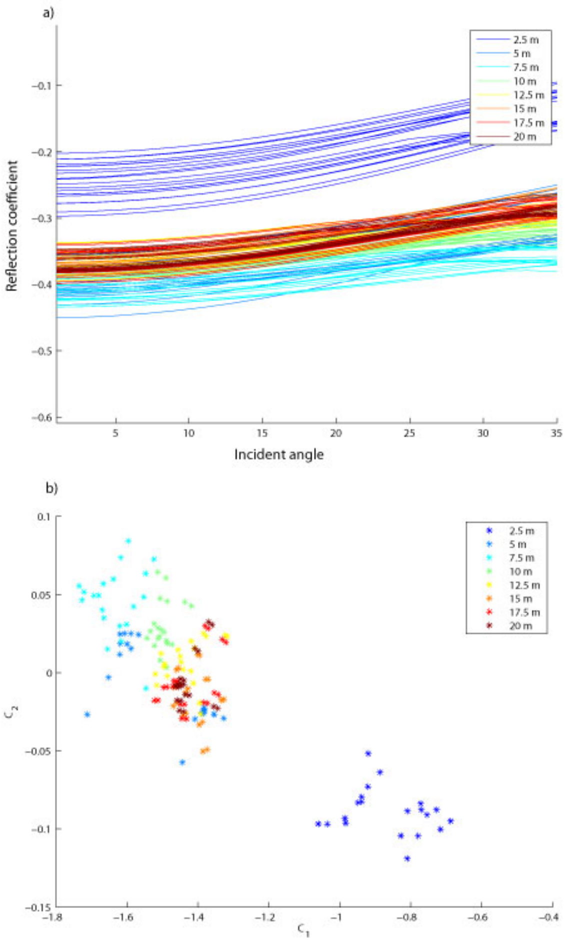

Figure 6. *Top: Reference AVO curves for varying thicknesses (colour-coded) of a CO_2 layer beneath a 5-m thick shale layer. Bottom: Cross-plot of coefficients C_1 and C_2 of the basis functions describing the reference curves in (a).*

Figure 6 shows the cross-plot of C_1 and C_2 for these reference curves. The coefficients of the 2.5-m and 7-m thick layers are clearly separate from each other and from the other thicknesses, and can thus be used as a classification criterion. The other coefficients plot in close proximity to each other and classification is more difficult. For thicknesses above 12.5 m, the coefficients barely change and plot on top of each other. Provided that estimated velocities, densities and overlying layer thicknesses are sufficiently precise, we would expect that C_1 and C_2 obtained from real data fall on the modelled values. However, due to the non-uniqueness of the modelled coefficients, classification would be limited, particularly for thicknesses larger than the tuning thickness. Work to obtain better estimates of parameters and to classify real data from the Sleipner plume is ongoing.

Extrema signal classification. The flow of CO_2 within the Utsira Sand is mostly buoyancy driven and as observed on the time lapse seismic, several thin intra-reservoir mudstones significantly retard the migration of CO_2 towards the reservoir top. In order to improve the predictive qualities of reservoir flow models, it is important to map the geometry of these mudstones as accurately as possible. This is a challenging task, because well-logs show that the mudstones are generally not much more than a metre thick and thus hardly seismically detectable.

Up to now, in the absence of better constraints, geological models of the Utsira Sand have assumed that the deeper mudstone layers are structurally conformable with the base of the shallowest intra-reservoir mudstone, which at more than 5m thick, is seismically detectable. This is clearly a simplification, so renewed effort is being made to detect and map the intra-reservoir mudstones by applying a technology called extrema classification (Borgos et al. 2003). Data preconditioning comprised multiple removal by predictive deconvolution, followed by a noise reduction scheme that smoothed the seismic signal along the reflectors, while preserving stronger discontinuities that might correspond to faults. Extrema classification applied to the 1994 (baseline) dataset was used to generate horizon patches for all events (peaks and troughs). Horizon patches characterized by similar seismic waveform attributes at the extrema were then aggregated into fully interpreted horizons. These horizons are tentatively inferred to correspond to the thin intra-reservoir mudstones.

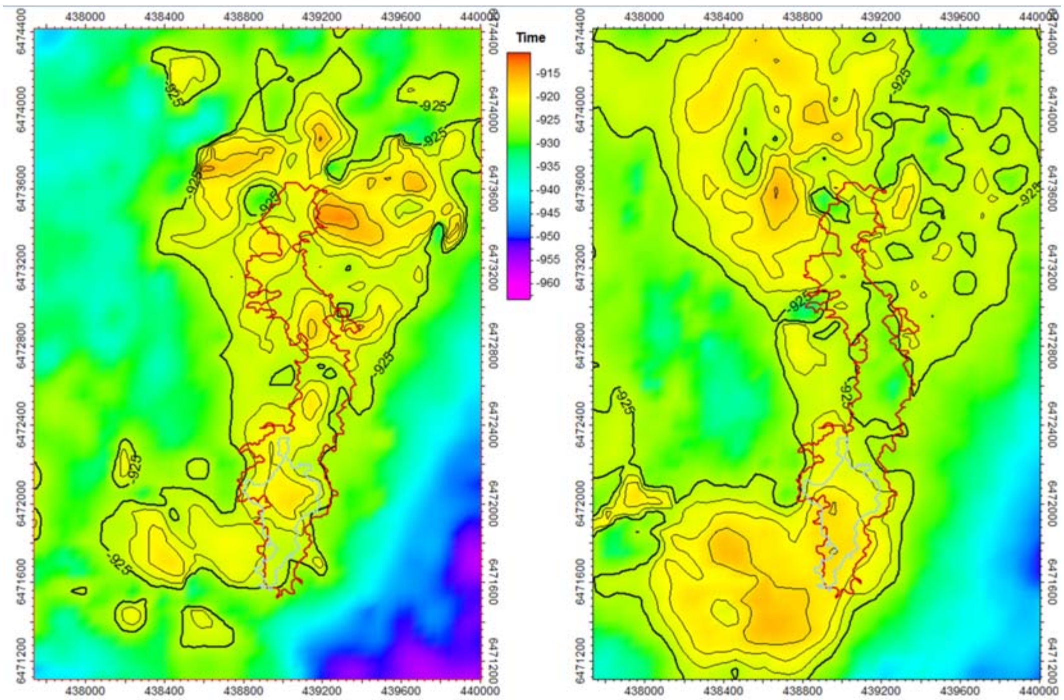

Figure 7. *Left: Map view of a new intra-reservoir horizon interpreted from extrema analysis of the 1994 baseline dataset (depth contours in black with colourscale). Superimposed are the outline of the 2001 (light blue) and 2006 (red) CO_2 layers ponding beneath this surface. Right: The corresponding surface with a topography which is conformable with the shallowest intra-reservoir mudstone.*

A horizon interpreted by extrema classification is shown in map view (Figure 7). Superimposed on this are the limits of the CO_2 layer trapped beneath the horizon for the 2001 and 2006 surveys. It is clear that development of the CO_2 layer broadly follows the topography of the horizon. The mapping match is not perfect suggesting that layer spreading may also influenced by other factors such as variable permeability or porosity. Yet, it seems clear that the new horizon interpretation gives a better result than mere translation of the topography of the shallowest intra-reservoir mudstone. It is hoped that more intra-reservoir horizons can be detected and mapped in this way and may perhaps contribute to improved reservoir flow modelling.

The path forward. Quantitative analysis of the time-lapse seismic at Sleipner is ongoing. The prevalent thin-layer (tuned) reflectivity renders conventional application of techniques such as AVO and trace inversion challenging. Quantitative interpretation can yield direct estimates of CO_2 layer thicknesses, which, when integrated with spectral decomposition and constrained AVO can yield improved estimates of layer velocities. Recent work on the Sleipner data using whole waveform inversion in the frequency domain has the potential to further improve resolution of the inversion tool. Work on common-focus point processing and velocity tomography is also in progress.

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Corresponding author: rach@bgs.ac.uk

Andy Chadwick has an MA in Geology from Oxford and a DSc in Geophysics from Durham. He leads the CO_2 Storage Research Team at the British Geological Survey (BGS) and is working on most aspects of CO_2 storage.

Nicolas Delépine is a research geophysicist in the fields of seismic modelling and inversion at IFP. He received a diploma in geophysics from the EOST-IPG, Strasbourg and a PhD from Ecole des Ponts Paris Tech.

Vincent Clochard is a research geophysicist at IFP. He obtained his PhD in applied geophysics from the French Petroleum Institute. He worked on 3DVSP and pre-stack depth imaging and is now working on stratigraphic inversion.

Karine Labat graduated from the Nancy School of Geology and obtained an MSc in Geophysics from the IFP School. She now works for the inversion team at IFP as a research geophysicist.

Gareth Williams has a PhD in geophysics. He leads the reservoir geology team at BGS. He specialises in structural geology and many aspects of seismic geophysics.

Susan Sturton has a PhD and postdoctoral experience in modelling volcanoseismic events and is currently a research scientist at SINTEF Petroleum Research working on AVO analysis and CSEM modelling and inversion.

Maike-L. Buddensiek has a PhD from the Free University of Berlin and the GFZ Potsdam, and now works for SINTEF Petroleum Research on AVO analysis and seismic physical modelling.

Menno Dillen has a PhD in geophysics from Delft University of Technology and is Research Manager at SINTEF Petroleum Research. His main interests are time-lapse seismology, wave equation imaging, rock physics and CO_2 storage monitoring.

Michael Nickel holds a PhD in engineering cybernetics. He works for Schlumberger Stavanger Research developing methods for reservoir characterization and monitoring.

Anne Louise Lima holds an MSc in statistics from the Norwegian University of Science and Technology. She now works as a research scientist in Schlumberger Stavanger Research, focusing on automated seismic interpretation and classification.

Rob Arts is a technology manager at TNO and has a part-time position as professor at the Delft University of Technology in monitoring technology. Rob has been active in the field of CO_2 storage since 1997 particularly in the monitoring of Sleipner.

Filip Neele holds a PhD in seismology from Utrecht University. He has been active in the field of CO_2 storage at TNO since 2006, with monitoring, storage capacity and CCS development as the main elements in his work.

Giuliana Rossi has an MSc in geology and a PhD in geophysics. She is currently a senior researcher at the Italian National Institute for Oceanography and Applied Geophysics (OGS).