Thin layer detectability in a growing CO₂ plume: testing the limits of time-lapse seismic resolution

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Abstract

Time lapse seismic surveys covering the CO₂ injection plume at Sleipner are used to test novel techniques which estimate the thickness of a spreading CO₂ layer. Utilising the spectral content of the data, the methods extend the limited vertical resolution encountered with time domain data.

Spectral decomposition using the smoothed pseudo Wigner-Ville distribution extracts monochromatic reflection amplitudes from the topmost CO₂ layer and is used to assess the lateral variation in peak tuning frequency. This provides a direct proxy for temporal thickness which show consistency with true layer thicknesses derived from structural analysis.

A spectral inversion method is also applied to a subset of the upper layer, with limited success. It is noted that high signal-to-noise ratios and the absence of overlying and underlying reflections are required to utilize the technique fully.

Keywords: Sleipner; Time-lapse; Seismic; Spectral decomposition; Spectral inversion; Resolution

1. Introduction

CO₂ produced from the Sleipner gas field is being injected into the Utsira Sand at rate of ~1 Mt/year. Injection of dense phase CO₂ began in 1996, close to the base of this highly porous and permeable...
Cenozoic saline aquifer. The reservoir consists predominantly of clean unconsolidated sand, but a number of thin, intra-reservoir, mudstone layers are evident in wireline logs from adjacent wells.

An initial, pre-injection, baseline 3D seismic survey was shot in 1994 and has been followed by further time-lapse 3D seismic surveys over the injection site in 1999, 2001, 2004, 2006, 2008 and 2010 to monitor the growth of the expanding plume. Time-lapse 4D seismic monitoring has introduced a new dimension to detection, measurement and imaging of the subsurface. The technique is particularly applicable to CO₂ monitoring since the injection of CO₂ produces significant acoustic impedance changes. As such, repeat surveys produce a noticeable change in the seismic response (Fig 1).

The plume is imaged as a sequence of nine high amplitude sub-horizontal reflectors within the aquifer, brought about as the buoyant CO₂ spreads passively beneath the low permeability mudstone layers. An increase in the amplitude of the upper reflections is observed on later surveys as more CO₂ reaches the top of the Utsira Sand whilst underlying reflections suffer an attenuation of their signal (Fig 1). This makes quantitative analysis of the whole plume using only reflection amplitudes difficult, since reflections are thought to represent the tuned response from thin layers of CO₂ trapped beneath the mudstone baffles. The layers themselves are too thin to be resolved seismically due to the limited spectral content of the source wavelet. Since no log records are available from within the plume itself, accurate mapping of intra-plume layer thickness has proved, and remains, a challenge. Therefore, particular interest is focused on the topmost plume reflection, from the reservoir-topseal interface, since this is clearly imaged in all vintages and displays no attenuation from overlying CO₂. Fig 1 shows the total reflection amplitude of the spreading topmost layer and highlights the elongate distribution of the CO₂ which ponds buoyantly beneath the topseal topography.

Fig. 1. Upper panels display a cross section from successive time-lapse seismic surveys at Sleipner. The strong reflections, absent in the 1994 data, denote the growing CO₂ plume. The topmost plume reflection is highlighted with an arrow. The lower panels show the total reflection amplitude of the expanding topmost layer in plan view.
An estimate of CO$_2$ thickness distributions in the growing topmost layer can be derived from structural analysis. The top Utsira Sand topography from the 1994 baseline survey is utilized together with maps of the spatial CO$_2$ extent from subsequent surveys. Measuring the difference in elevation between the topseal relief, shown in Fig 2 (a), and an interpolated flat CO$_2$ – water boundary provides an estimate of the layer thickness [1][2]. Fig 2 (b) displays the temporal thickness distribution for the 2006 dataset after application of a 25 x 25 m smoothing filter. Comparison with the reflection amplitude map (Fig 1) shows a reasonable agreement between amplitudes and temporal thicknesses.

From an imaging perspective, the effective maximum resolution corresponds to the tuning thickness (peak wavelength / 4), beneath which the peak-to-trough time separation remains constant and changes in the layer thickness can no longer be mapped. Frequency information present in seismic data however can be used to estimate the temporal thickness of layers which are too thin to be resolved in the time domain. A number of advanced seismic techniques have evolved in order to overcome this imaging limitation. In this study, two of these solutions are applied to the problem of analyzing the thin topmost CO$_2$ layer imaged on the Sleipner data: spectral inversion and spectral decomposition.
2. Spectral decomposition

Discrete Fourier components extracted from windowed seismic data can be used to estimate the temporal thickness of reflectors below the tuning thickness. The temporal thickness (T) can be derived from the period of notching in the frequency spectrum [3] using the relationship \( T = 1/2f \), where \( f \) represents the tuning frequency (frequency of the peak amplitude in a time-frequency gather). A small analysis window is required to isolate reflections from the individual CO\(_2\) layers at Sleipner, consequently conventional time-frequency analysis techniques suffer from resolution problems: a narrow analysis window localises the spectrum in time but provides poor frequency resolution. This study employs the quadratic Smoothed Pseudo Wigner-Ville Distribution (SPWVD) to quantify tuning in the top-most layer of the plume. Careful analysis of synthetic seismic models has demonstrated that the SPWVD has optimum time-frequency resolution for imaging the CO\(_2\) layers at Sleipner [4][5].

The Wigner-Ville Distribution \((W_{x(t,\nu)}^{x(t,\nu)})\) is constructed by computing the auto-correlation over all possible lags at each time sample (the local auto-correlation function) and transforming into Fourier space.

\[
W_{x(t,\nu)}^{x(t,\nu)} = \int_{-\infty}^{+\infty} x(t + \frac{\tau}{2}) x^*(t - \frac{\tau}{2}) e^{-\imath 2\pi \nu \tau} d\tau
\]

where \( t \) is time, \( \tau \) the lag, \( \nu \) the frequency and \( * \) represents complex conjugation.

This algorithm is a quadratic function and, consequently, discrete events in a time series produce cross-terms in the time-frequency distribution. The cross-terms can be reduced by smoothing with an appropriate filter kernel along the time \( g(x-t) \) and frequency \( h(\tau) \) axes to give the Smoothed Pseudo Wigner-Ville Distribution.

\[
SPWVD_{x(t,\nu)}^{x(t,\nu)} = \int_{-\infty}^{+\infty} h(\tau) \int_{-\infty}^{+\infty} g(x-t) x(t + \frac{\tau}{2}) x^*(t - \frac{\tau}{2}) dt e^{-\imath 2\pi \nu \tau} d\tau
\]

Discrete frequency cubes were generated using the SPWVD from 3D seismic data acquired in 1994, 2001, 2004, 2006 and 2008. The 2001 and 2004 data were re-processed in 2006 using a joint time-lapse scheme whilst a similar processing flow was also applied to the 2008 vintage data. The topmost layer of CO\(_2\) in the plume was picked on each frequency cube and RMS amplitude slices on the pick were extracted and mapped. Spectral balancing is required to correct for the fact that the frequency spectrum of the seismic wavelet is not flat. Because geological stratigraphic sequences are assumed to have a ‘white’ frequency spectrum, it has been assumed that geological tuning of each discrete frequency band occurs somewhere in the seismic volumes. This means that the wavelet spectrum can be balanced by equalizing each frequency slice according to its maximum measured amplitude [3]; the scaling functions used to balance were derived from the discrete frequency – maximum amplitude curves calculated for each time-lapse data set (Fig 3).
Spectrally balanced reflection amplitudes for the topmost layer of each seismic vintage are shown in Fig 4 which illustrates the development of the CO₂ distribution. It is apparent that by 2001 CO₂ had begun to fill four prominent domes in the topography (marked 1 to 4) passively infilling the topography such that the CO₂ layer thickens beneath domes and thins beneath depressions. In the simplest terms, higher frequencies will tune over shorter time delays and so a decreasing tuning frequency can be considered as a proxy for an increasing CO₂ layer thickness. As such, the dominant frequency at the centre of an accumulation should shift to lower values with time. This effect is seen in Dome 2, where the highest amplitudes are seen at the highest frequencies in 2001 and 2004. By 2006 the centre of the culmination appears to tune at 60 Hz and it is lower still (40 Hz) in 2008, with higher frequency tuning around the margins. The centre of Dome 1 displays a similar pattern with high frequency tuning in the earlier vintages reducing progressively to a lower tuning frequency.

Dome 3 does not seem to show this effect and amplitude decreases are seen across the frequency range. Possible explanations for this are that Dome 3 acts as a temporary holding reservoir for mobile CO₂, which then preferentially migrates northwards, or the extent of the structure has been overestimated. Conversely, the prominent north-trending ridge of CO₂ encompassing Dome 4 shows particularly distinctive tuning effects consistent with passive gas accumulation beneath topseal topography. The topographic high point (located toward the centre of the white box) is characterised by tuning at lower frequencies (~50 Hz) when compared to the flanks of the culmination (~65-70 Hz). CO₂ has reached the southern flank of Dome 4 by 2001 (Fig 4 (a)), although distinctive tuning effects are not observed until 2004. The culmination of the dome generally has low amplitudes at all frequencies, suggesting that little gas has filled the structure in the early seismic vintages. However, the southern flank of the culmination shows higher amplitudes at frequencies greater than 60 Hz. By 2008, distinctive tuning effects have developed around the apex of the dome. The centre of the accumulation tunes at frequencies ≤ 50 Hz, with strong tuning on the northern and southern flanks at ~70-80 Hz.
Fig. 4. Normalized reflection amplitudes for discrete frequency slices from four time-lapse vintages at Sleipner.
Taking the time-lapse spectrally balanced distributions and normalising spatially with the equivalent response from the 1994 baseline dataset should remove any spurious spectral effects generated as a consequence of the geology. Following this procedure, a loop through the discrete frequencies to determine the spectral component with the greatest change at each location is undertaken. This component corresponds to the tuning frequency and from this an estimate of the temporal thickness of the CO₂ layer can be made.

Using a calculated layer velocity of 1420 m/s, with the assumption of homogenous fluid substitution [4], it is possible to calculate true layer thicknesses across the extent of the topmost layer; shown in Fig 5 (a) for the 2006 vintage. Calculated thicknesses show a surprising degree of continuity and with no filtering applied. A comparison with the thickness map derived from structural analysis Fig 5 (b) shows a reasonable agreement and it is noticeable that few spurious results are seen outside the layer boundaries. The locations of peak layer thicknesses are well correlated and the northern section of the ridge displays excellent agreement between the methods. The equivalence of the two thicknesses plots in Fig 5 provides a reassurance as to the general validity of the method. It is likely that in future CO₂ injection scenarios the overburden will not offer such clarity of topographic relief as that encountered at Sleipner. The new
scheme therefore offers an approach to estimating CO\textsubscript{2} layer thicknesses which is applicable to different, and geologically more complex, injection sites.

3. Spectral inversion

Spectral inversion is a technique which uses spectral decomposition to improve imaging of thin layers whose thickness is below tuning thickness. Absolute temporal layer thickness can be determined alongside the respective reflection coefficients of the upper and lower layer interfaces.

Application of windowed Fourier transform and complex spectral analysis enables the formulation of an inversion algorithm. The method for two reflections uses the constant periodicity of the amplitude spectrum for a single layer of thickness, \( T \). The cost function, defined by Puryear and Castagna [6]:

\[
G(f) \frac{dG(f)}{df} + 2\pi Tk \sin(2\pi fT)
\]

is evaluated across a range of frequencies. \( G(f) \) is the magnitude of the amplitude spectrum and \( k = r_o^2 - r_e^2 \) where \( r_o \) and \( r_e \) are the odd and even components of the reflection coefficient pair. Finding the global minimum of the cost function by scanning a reasonable model space in \( T \) and \( k \) gives the desired solution.

The technique has been successfully applied to a synthetic wedge of CO\textsubscript{2} and to pre-stack seismic data [7]. This study aims to isolate a reflection from the top and base of the topmost CO\textsubscript{2} layer at Sleipner and to utilize the method to estimate a layer thickness. In previous synthetic two-layer cases the method is shown to be reliable at signal-to-noise ratios of greater than 40 if the extracted trace is subjected to minimal superposition effects from additional reflections. This isolation of response is the primary issue hindering the widespread use of the technique for real data.

Analysis was focused on the N-S trending ridge just north of Dome 4 in the 2006 dataset, see white box highlighted in Fig 5 (a), where the underlying CO\textsubscript{2} layers do not extend beneath the topmost layer.

Spurious results account for ~10\% of the temporal thickness estimates and these have been removed and re-gridded by interpolating with the remainder of the data. Fig 6 shows the response from the spectral inversion method alongside the spectral decomposition result. A broad agreement is seen in the relative thickness of the advancing CO\textsubscript{2} layer. However the lack of success across the whole CO\textsubscript{2} layer with the spectral inversion scheme makes it difficult to justify as an approach to layer thickness estimation.
4. Conclusions

Carefully acquired and processed 4D seismic data is capable of resolving small amounts of CO\(_2\) in the subsurface due to the significant changes in acoustic impedance produced during fluid substitution. However, quantification of the vertical extent of an expanding CO\(_2\) layer is challenging. This study has approached the challenge in two ways; both pushing the spectral content of the data to its limits. Using the smoothed pseudo Wigner-Ville distribution to extract monochromatic reflection amplitudes from the topmost CO\(_2\) layer at Sleipner, sufficient temporal and spectral resolution is available to allow extraction of the tuning frequency from a single CO\(_2\) layer. This allows the temporal thickness to be derived to a reasonable degree of accuracy.

This study has shown how the extracted thickness distribution shows a satisfactory correlation with previous thickness estimates derived from structural analysis. This is a noteworthy result since future CO\(_2\) storage sites are unlikely to offer such a well constrained overburden topography as that at Sleipner, making spectral decomposition a useful tool in assessing layer thicknesses in more complex geological environments. Studies are currently underway utilizing the spectral decomposition algorithm at further CO\(_2\) injection sites.

The use of a two-layer spectral inversion algorithm to assess the thickness of a thin CO\(_2\) layer has shown mixed results. The relative thicknesses extracted correlate reasonably well with those derived from spectral decomposition and structural analysis but the limited subsurface volume exploitable by the technique makes its continued use unlikely. The computationally heavy multi-layer spectral inversion algorithm [6] might offer a better chance of success across the whole plume.
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References


