Synthetic versus real time-lapse seismic data at the Sleipner CO_2 injection site.

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Summary

CO_2 has been injected into the Utsira Sand at Sleipner since 1996, with more than 9 million tonnes currently in the reservoir. Seismic monitoring surveys to follow the migration of the CO_2 in the reservoir have been carried out in 1999, 2001, 2002, 2004 and 2006. The CO_2 plume is imaged on the seismic data as a prominent multi-tier feature, comprising a number of bright sub-horizontal reflections, growing with time, interpreted as arising from up to nine discrete layers of high saturation CO_2, each up to a few metres thick. Quantitative seismic interpretation of the time-lapse data has included synthetic seismic modelling to derive CO_2 distributions in the reservoir. Convolution-based modelling has shown that seismic reflection amplitudes are broadly related to layer thickness via a tuning relationship. However acquisition geometry, lateral velocity changes, mode conversions and intrinsic attenuation are all likely to affect amplitudes and need to be incorporated for a rigorous quantitative analysis. A first attempt to incorporate some of these effects, through more realistic pre-stack elastic modelling and processing, is presented here. Both the acquisition geometry and the processing sequence of the synthetic data are comparable to the real field data. Results support the basic amplitude-thickness relationship.

Introduction

Carbon dioxide injection at the Sleipner field in the North Sea commenced in 1996, the first industrial scale CO_2 injection project specifically for greenhouse gas mitigation. CO_2 separated from natural gas is being injected into the Utsira Sand (Figure 1), a major saline aquifer of late Cenozoic age (Zweigel et al. 2004). The injection point is at a depth of about 1012 m bsl, some 200 m below the reservoir top. Baseline 3D seismic data were acquired in 1994 with repeat surveys in 1999, 2001, 2002, 2004 and 2006, with, respectively 2.35, 4.26, 4.97, 6.84 and 8.4 million tonnes of CO_2 in the reservoir. The CO_2 plume is imaged on the seismic data as a prominent multi-tier feature, comprising a number of bright sub-horizontal reflections, growing with time. The reflections are interpreted as arising from up to nine discrete layers of high saturation CO_2, each up to a few metres thick (Chadwick et al. 2004; 2005). The layers have mostly accumulated beneath thin intra-reservoir mudstones, with the uppermost layer being trapped beneath the reservoir caprock. However, the structural geometry of the intra-reservoir mudstones is not well known because they are too thin to be imaged on the baseline dataset.

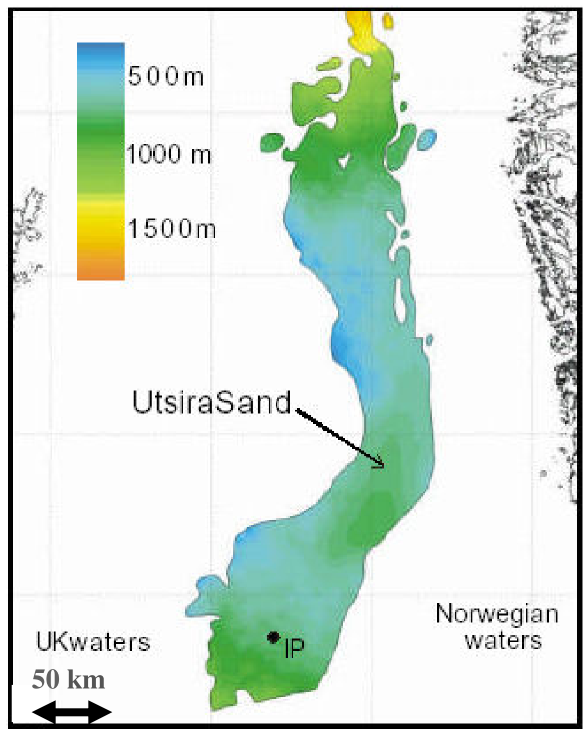

Figure 1: Depth map of the Utsira Sand with the CO_2 injection point (IP) indicated. Note that the area currently occupied by the CO_2 is less than 3 km^2.

Previous interpretations of the seismic data (Arts et al., 2004; Chadwick et al. 2004; 2005) have estimated the thickness of the individual high saturation CO_2 layers from a seismic amplitude – thickness tuning relationship. In this paper the 1999 seismic data is evaluated by pre-stack elastic modeling, applying realistic field acquisition geometries. Results of the modelling and acquisition effects on the seismic imaging are demonstrated.

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Reservoir description

Around Sleipner, the Utsira Sand is a highly porous (35-40%) weakly consolidated sandstone at depths between about 800 m and 1100 m, with a thickness of about 250 m around the injection site. The overburden comprises a predominantly mudstone-siltstone sequence up to the seabed with a sealing unit of more than 200 m of silty mudstone directly above the reservoir. Within the reservoir itself, thin mudstone layers in the order of 1 m thick have been identified (Gregersen et al.1997; Zweigel et al. 2004), which act as baffles to the upward migration of the CO_2 (Figure 2).

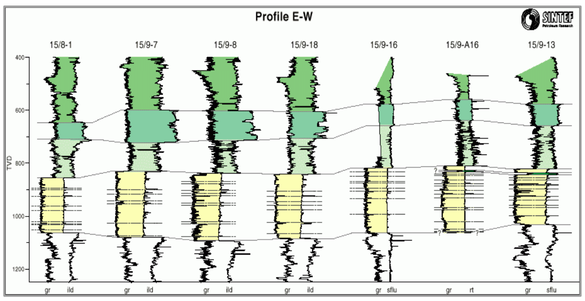

Figure 2: East-West correlation panel of the different well logs (gamma ray and resistivity logs) penetrating the mudstone-siltstone overburden (in green) and the Utsira Sand reservoir (in yellow). Note the uncorrelated thin shale layers appearing as peaks in the Utsira reservoir.

Seismic Modelling

A 2D fully elastic finite-difference wave propagation simulation has been used here. Input data for the modelling comprised a 2D north-south cross-section through the central part of the 1999 plume (Figure 3).

The section is extracted from the CO_2 saturation model of Chadwick et al. (2005), modified for partially 'patchy' mixing of dispersed CO_2. Although the model has some limitations, mostly in the simplified vertical distribution of dispersed CO_2 in between the main reflective layers, it does give a reasonable picture of likely CO_2 distributions within the plume. The model comprises a set of layers: seawater, overburden, caprock mudstone, intra reservoir sand layers (variably saturated with CO_2), intra-reservoir mudstones and sub-reservoir mudstone. Layer parameters comprise x,y,z co-ordinates with linked properties (CO_2 saturation, Vp, Vs and density). A key simplifying assumption, in terms of model building and interpretation, is that the intra-reservoir mudstones are all parallel to the reservoir top. This is undoubtedly incorrect, but in the absence of specific information on mudstone geometry, the model is considered suitable for realistic modelling of both the plume and also reflections beneath it.

Synthetic shots were generated along the north-south cross-section, extended at both ends by an additional 2 km leading to a 8 km long model. Modelling was based on acquisition parameters similar to the real time-lapse data.

Table 1: Acquisition parameters used for the synthetic modelling:

Receiver spacing = 25 m
Source spacing = 25 m
CDP spacing = 12.5 m
Cable length = 3600 m
Number of receivers = 145
Distance source – 1st receiver = 165 m

Synthetic shot gathers differ markedly, depending on the relative positions of the recording spread and the subsurface plume. Away from the plume, events on the gather arise just from the model geological interfaces, and are regular and hyperbolic. Over the plume itself, reflectivity within the reservoir is increased due to the presence of CO_2, but moveout is much more irregular with timeshifts introduced by the lateral changes in velocity (Figure 4).

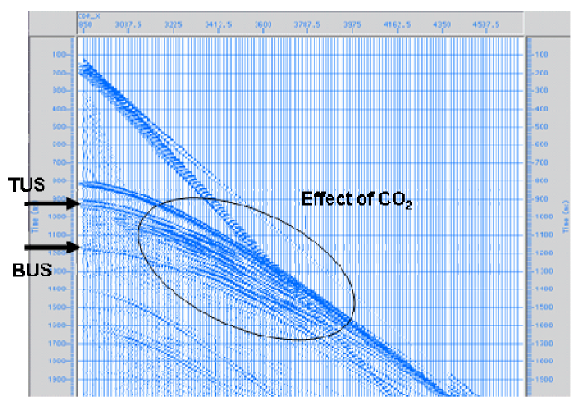

Figure 4 Synthetic shot gathers generated by elastic pre-stack modelling. Source and streamer are above the CO_2 plume which is imaged on mid-offset traces. Note enhanced reflectivity in the reservoir, but reduction of coherency in deeper reflections due to lateral velocity changes TUS = Top Utsira Sand; BUS = Base Utsira Sand.

The CO_2 plume can be followed through the different shots and CMP gathers and it is clear that the width of the plume "reflection zone" is much less than the spread length. This results in non-hyperbolic move-out that will significantly degrade stack response, producing a false attenuation of reflections beneath the CO_2 plume on stacked datasets.

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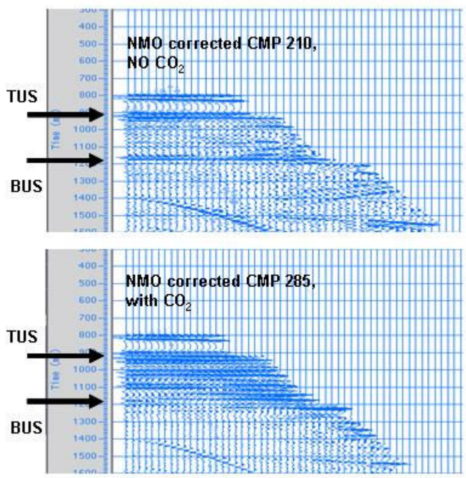

Figure 5: Comparison between a synthetic CMP gather without CO_2 (upper) and with CO_2 (lower) present.

After NMO correction (Figure 5) the data were stacked and migrated using the NMO-velocity model, with application of a phase shift similar to the real data, to produce a migrated 2D seismic section. Results are very comparable to the observed data (Figure 6).

Interpretation results

The effect of the CO_2 on the seismic data at Sleipner is evident with two main effects determining the seismic response:

- The negative seismic impedance contrast between mudstone and underlying sand becomes more negative (larger in absolute value) when CO_2 is present in the sand.
- The seismic response is a composite tuning wavelet caused by interference from sequences of water-saturated sand, mudstone, CO_2 - saturated sand and water-saturated sand again.

The first effect leads to stronger negative seismic amplitudes as for a classical “bright spot”. The second effect (tuning) can lead to destructive or constructive interference depending on the thickness of the CO_2 layer. Simple convolutional seismic modeling has shown that as the thickness of the CO_2 column increases from 0 to 8 m a gradual increase of the (negative) amplitude is observed (Arts et al. 2004). Maximum reflection amplitude corresponds to a CO_2 thickness of about 8 m, the so-called ‘tuning thickness’

From the migrated synthetic data an interpretation of the individual seismic reflectors has been carried out similar to the interpretation of the observed datasets. Reflection amplitudes have been mapped and compared to the thickness of the individual CO_2 layers from the input model, the comparison focused on three different levels in the plume. Overall the synthetic amplitudes show a good correlation with model layer thickness and corroborate the use of a seismic amplitude – CO_2 thickness relationship for quantitative analysis.

Conclusions

Interpretation of the Sleipner time-lapse seismic data has not been straightforward due to the large velocity contrast between CO_2 - saturated and water-saturated reservoir rock which assists, but also complicates seismic imaging. Furthermore, since the thin intra-reservoir mudstones cannot be identified on the baseline seismic data, precise details of internal reservoir geometry are not known and the construction of an accurate reservoir flow model is very challenging. To help overcome these problems synthetic seismic modelling has been used to elucidate CO_2 distributions in the reservoir, though only for the 1999 dataset so far.

Simple convolution-based acoustic modelling indicated that a direct relationship between seismic amplitudes and CO_2 layer thickness should exist. This assumption has been further investigated by full wave equation elastic modelling followed by a basic processing sequence, including migration similar to that applied to the real data. Comparing the processed synthetic seismic data with the convolution synthetic seismic data significant differences can be observed in terms of lateral coherency and horizontal resolution, but not so much in terms of amplitude information. This observation has strengthened our confidence in the seismic amplitude versus high concentration CO_2 accumulation thickness.

Acknowledgments

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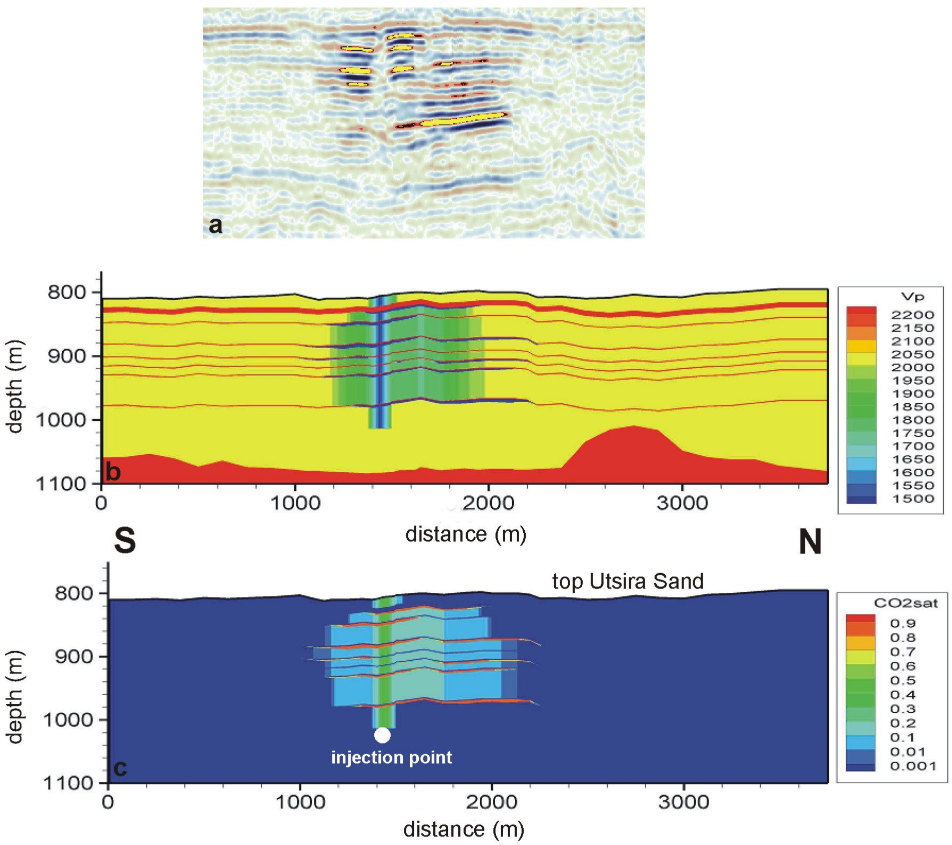

Figure 3 Detailed model of the Sleipner plume in 1999 derived from acoustic modelling. Seismic inline 3838 (top), modelled Vp (centre), modelled CO_2 saturation (bottom). Note the vertical column of velocity pushdown and reduced reflectivity interpreted as a vertical feeder chimney of higher saturation CO_2.

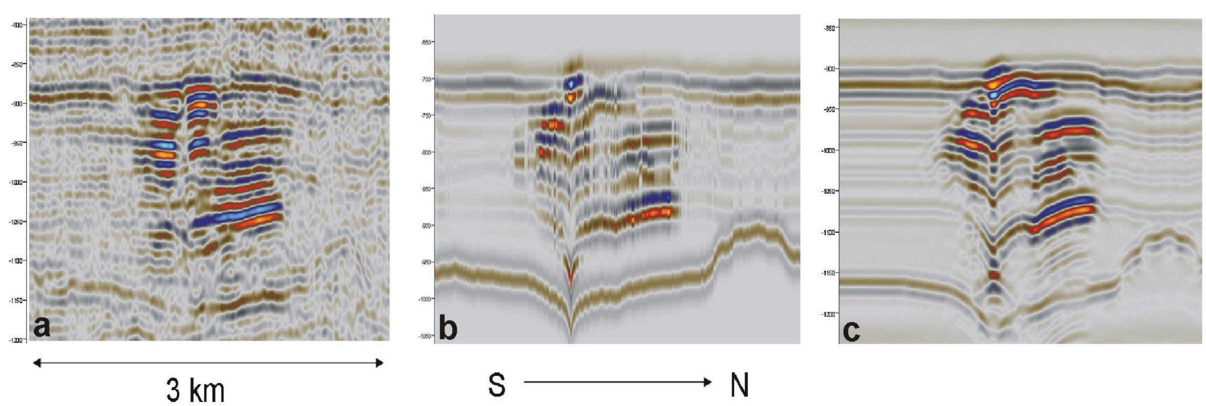

Figure 6 A comparison between a) the observed inline from the 1999 seismic survey; b) the corresponding synthetic line obtained by convolutional modeling and c) the corresponding synthetic line after 2D elastic modelling and processing