Calibrating reservoir performance with time-lapse seismic monitoring and flow simulations of the Sleipner CO_2 plume

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Abstract
Since its inception in 1996, the CO_2 injection operation at Sleipner has been monitored by four repeat 3D seismic surveys. Striking time-lapse seismic images of the CO_2 plume have been obtained, but some aspects of reservoir structure and properties remain imperfectly understood. The topmost layer of the CO_2 plume can be most accurately characterized, its rate of growth quantified, and CO_2 flux at the reservoir top estimated. The latter has been quite stable since 2001, which suggests that transport through intra-reservoir mudstones is via a limited number of discrete pathways that became established quite early in plume evolution. This important constraint on reservoir performance can help calibrate longer-term predictive models of plume evolution.

Keywords: Sleipner, CO_2, storage, seismic monitoring, flow simulation, climate change.

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, a major saline aquifer of late Cenozoic age [1]. 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 (2.35 million tonnes of CO_2 injected), 2001 (4.26 Mt) and 2002 (4.97Mt). Preliminary data from a 2004 survey (6.84 Mt) are also available courtesy of the Sleipner partners.

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 (Figure 1a). The reflections are interpreted as arising from up to nine discrete layers of high saturation CO_2, each up to a few metres thick. The layers have mostly accumulated beneath thin intra-reservoir mudstones (Figure 1b), with the uppermost layer being trapped beneath the reservoir caprock.

Quantitative analysis [2,3] has shown that while the seismic images are consistent with the known injected amounts of CO_2, they do not provide a unique verification of complete reservoir behaviour. Significant uncertainties remain, particularly regarding temperatures in the plume, and the fine-scale distribution of dispersed CO_2 in between the reflective layers. Similarly, reservoir flow simulations have reproduced the current development of the CO_2 plume as a multi-tier layered structure. However because the structural geometry of the sealing intra-reservoir mudstones is not precisely known, simulated layer thicknesses are not tightly constrained and have not yet been robustly matched to thicknesses obtained directly from the seismic data.

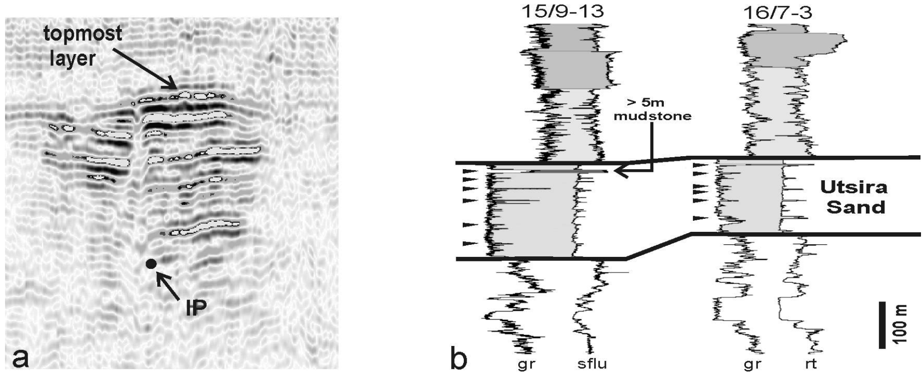

Figure 1 a) Seismic image of the Sleipner plume in 2002. IP = Injection Point. b) Geophysical logs through the Utsira Sand showing gamma-ray (gr) peaks corresponding to intra-reservoir mudstones. Note thicker (> 5m) mudstone near reservoir top.

The objective of this paper is to look at key aspects of the seismic data that constrain models of CO_2 migration through the reservoir, and to assess whether flow processes in the reservoir are understood to the extent that predictions and simulations of future, longer-term, plume behaviour are likely to be robust. A key issue in this respect is the possibility that CO_2, either physically or chemically, may alter the flow properties of the reservoir and caprock with time. Of particular interest would be evidence that CO_2 is progressively modifying the flow properties of the intra-reservoir mudstones that are likely to provide close analogues of the overlying caprock seal.

Quantifying the topmost CO_2 layer

The topmost CO_2 layer in the plume is of special interest for two main reasons. First, of all the layers in the plume, its thickness and volume can be quantified most accurately. Second, it represents the ‘end of the pipe’; its growth essentially measures the total upward flux of CO_2 through the reservoir and how this changes over time. Seismic reflection amplitude maps (Figure 2) show how the topmost layer has grown from two small patches in 1999 to an accumulation of considerable lateral extent by 2002. A north-trending linear prolongation is prominent, corresponding to CO_2 migrating northwards along a linear ridge at the reservoir top.

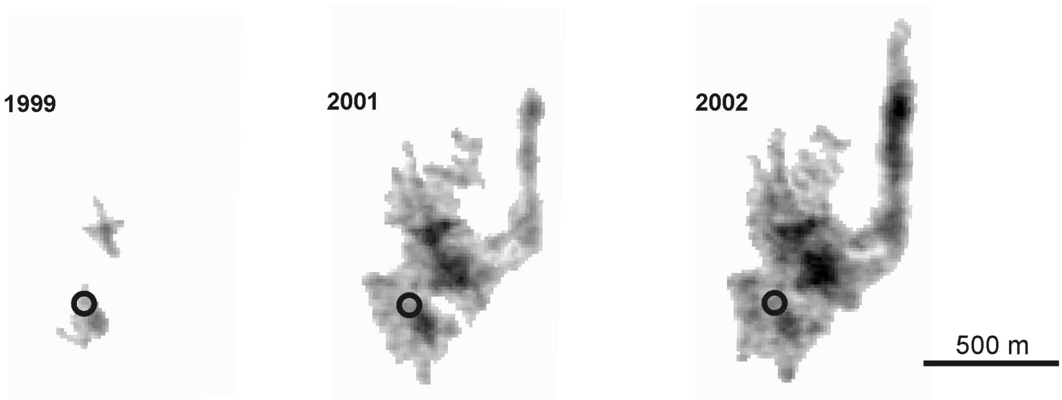

Figure 2 Growth of the topmost CO_2 layer mapped through time via seismic amplitudes (circle denotes location of injection point).

Layer thicknesses from seismic amplitude – thickness relationship (tuning)

Earlier work [2,3,4] has shown that layer reflectivity follows a thin-layer tuning relationship, with reflection amplitudes directly related to layer thicknesses. A theoretical amplitude – thickness relationship for the data was derived by scaling the tuning amplitude response from a thin-layer synthetic model to the maximum seismic amplitudes observed in the plume. This was used to transform observed amplitudes to layer thickness (Figure 3a). The 2004 dataset has not yet been matched to the earlier surveys so thicknesses could not be derived from the tuning relationship.

Layer thicknesses from structural analysis (static ponding)

An alternative, wholly independent way of obtaining layer thicknesses is by topographic analysis of the reservoir top. In map view, the outer limit of CO_2 reflectivity at this level corresponds to the CO_2 - water contact (CWC). By fitting a smooth 2D surface through the elevations of the CWC, the base of the topmost layer can be constructed (note that if the seismic were in depth not in time, and no fluid dynamic effects were tilting the contact, this surface would be horizontal). The thickness of the layer can then be calculated by subtracting the basal surface from the reservoir top (Figure 3b). Constructed layer thicknesses show a striking direct correlation with layer reflectivity (Figure 2), the main differences being that the seismic amplitudes have a smoother distribution and extend into localized areas where the static ponding distribution does not (see below).

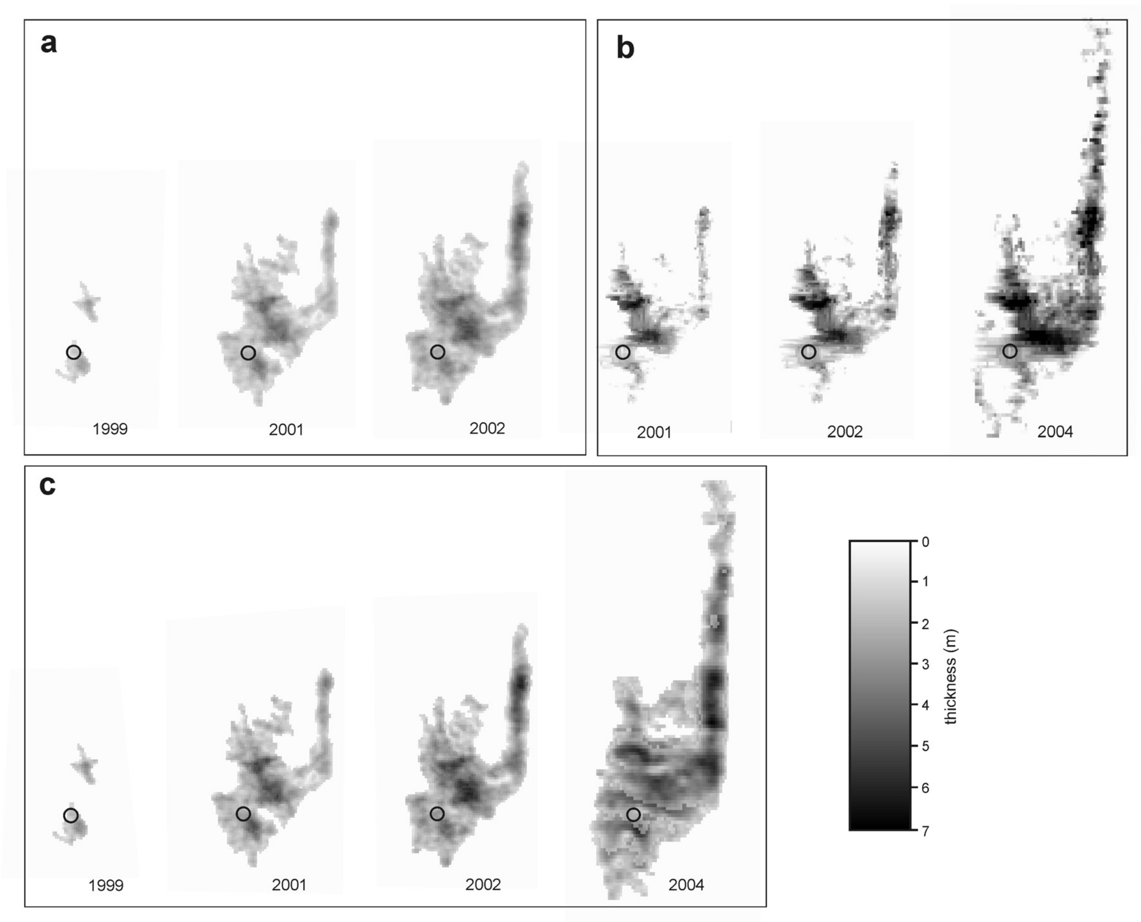

Figure 3 Topmost layer thicknesses a) Amplitude tuning b) Static ponding c) Amplitude and structure (circle denotes location of injection point).

Layer thicknesses from amplitudes calibrated to structural analysis (empirical)

The final method of thickness determination combines amplitudes and the structural analysis, by plotting, trace-by-trace, layer reflection amplitude for the topmost layer against its structurally derived thickness. Albeit with considerable scatter, a clear amplitude-thickness trend is evident for all of the survey vintages, similar, though not identical, to the synthetic tuning relationship. Using this trend to transform amplitudes to thicknesses gives a third set of thickness maps (Figure 3c).

The volume of CO_2 within the topmost layer was computed for the three methods of thickness determination (Table 1), assuming a mean sand porosity of 0.38 with saturations computed using a laboratory determined relationship between buoyancy forces and capillary pressure [3].

Table 1 Volume of CO_2 in topmost layer computed from three different methods

survey date	amplitudes and tuning (m^3)	static ponding (m^3)	amplitudes and structure (m^3)
1999	14573	12000	18086
2001	158087	127203	195831
2002	246914	222548	305418
2004		498027	611844

Volumes of CO_2 from the three thickness computations are broadly comparable but with some systematic differences. The static ponding construction allows no CO_2 to be present beneath the level of the CWC and represents the minimum amount of CO_2 commensurate with the observed gas-water contact. In reality the CO_2 layer is a dynamic entity with significant horizontal flow and perhaps supplied by multiple feeder chimneys, some of which may lie beneath topographic depressions in the topseal. These processes will lead to general layer thickening and allow deeper areas of caprock topography to be filled locally with CO_2 as suggested by the thicknesses derived from reflection amplitudes.

From the topmost layer volumes, the rate at which CO_2 has arrived at the top of the reservoir can be estimated. Taking, for example, the amplitude-structure thicknesses (Figure 3c), an estimated 1.8 x 10^5 m^3 of CO_2 arrived at the reservoir top between the 1999 and 2001 surveys, an average flux of ~250 m^3 per day. Between the 2001 and 2002 surveys ~1.1 x 10^5 m^3 of CO_2 arrived at the reservoir top, an average flux of ~450 m^3 day^{-1}. Between the 2002 and 2004 surveys a further ~3.1 x 10^5 m^3 of CO_2 arrived at the reservoir top, averaging ~400 m^3 day^{-1}. These volumes correspond to ~3.7%, ~6.2 % and ~6.5% of the total amount of CO_2 injected during the respective periods. Measurements on the 2004 dataset are, as yet, preliminary, but the data nevertheless indicate an early increase in flux rates followed by stabilization.

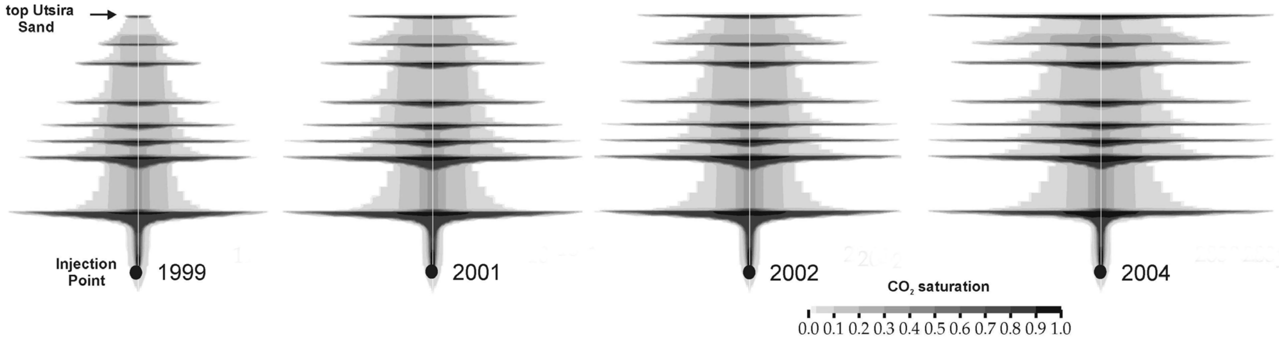

Figure 4 TOUGH2 flow simulation of the CO_2 plume assuming axisymmetric reservoir geometry

A reservoir flow model was set up to simulate plume growth (Figure 4). Reservoir geometry was taken to be axisymmetric (horizontal intra-reservoir mudstones), a deliberately minimal assumption justified by the lack of detailed information on intra-reservoir structure. Sand properties were based on laboratory measurements. Mudstones were assumed to be uniformly semi-permeable with relative permeability to CO_2 increasing steadily with CO_2 saturation. Specific mudstone flow properties were scaled to match the observed arrival of CO_2 at the top of the reservoir in 1999, just prior to the first repeat survey (Figure 4). From 1999 onwards, the flow simulation predicts a progressive increase of flux into the topmost layer (Figure 5). This is due largely to increased effective permeability within the central part of the plume as the semi-permeable intra-reservoir mudstones become progressively more saturated with CO_2 and, consequently, relative permeabilities to CO_2 flow increase.

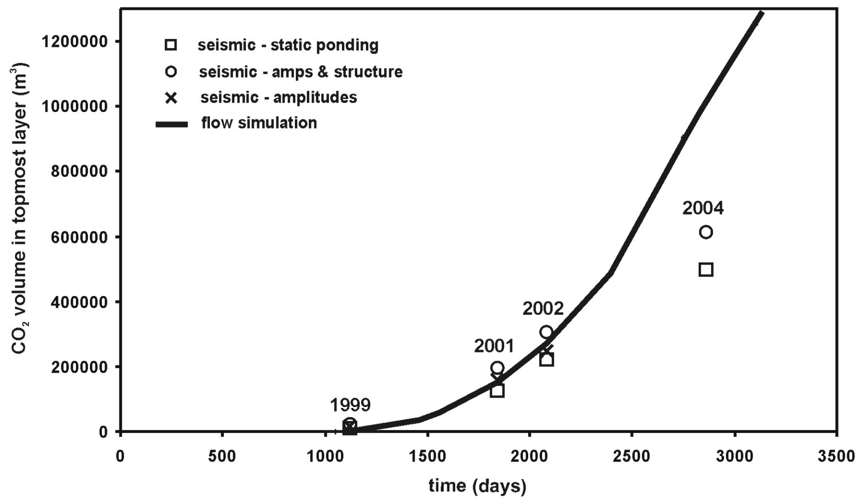

Figure 5 Growth of the topmost CO_2 layer: volumes derived from seismic analysis and from a TOUGH2 flow simulation with semi-permeable intra-reservoir mudstones.

Observed fluxes derived from the seismic data do not match the flow simulation. An early increase in flow rates gave way, from around 2001, to a more-or-less uniform flux (Figure 5). This is consistent with the early development and establishment of connected pathways through the intra-reservoir mudstones, but after this, no further change in effective permeability has occurred. This suggests that transport through the mudstones may not be by a semi-permeable process but rather via a number of discrete pathways, which became fully established quite early in plume evolution.

The number of such discrete pathways is uncertain. Growth of the topmost layer specifically depends on the transport properties of the relatively thick (>5m) mudstone immediately beneath (Figure 1). A single main feeder chimney has been proposed as responsible for most of the upward flux of CO_2 through the reservoir [2, 3]. Observed growth of the topmost layer is consistent with this. A number of additional discrete chimneys cannot be ruled out however, and would be consistent with the early development of the topmost layer as two seemingly distinct small accumulations (Figure 3a).

The observed discrepancy between simulated and observed fluxes at the reservoir top could be explained by one or more other processes. These include, migration of CO_2 out of the topmost layer into the overlying caprock, dissolution of CO_2 in the topmost later, and progressive permeability reduction in the intra-reservoir mudstones. Migration is considered to be unlikely, with no evidence thus far of changes in the caprock seismic signature above the plume. Significant dissolution at this early stage is also considered to be improbable. The third scenario raises the possibility that chemical reactions of CO_2 with mudstone mineralogies are producing new mineral phases capable of significantly reducing mudstone porosity and, by implication, permeability. Numerical modeling studies [5] have suggested that such reactions may have a significant effect on a twenty-year time-scale. However, other modelling results [6] indicate a slight porosity increase on the ten-year time-scale with porosity decrease not occurring until after 200 years or so.

Conclusions
Careful analysis of the topmost CO_2 layer in the Sleipner plume can closely constrain total upward CO_2 flux through the reservoir, a key indicator of whole-reservoir performance. Overall flow rates in the reservoir are largely controlled by the low permeability intra-reservoir mudstones. The analysis indicates that, following early and quite rapid establishment of flow pathways, mudstone flow properties have remained fairly stable. This improves confidence in likely caprock stability in the presence of CO_2, and more generally in the validity of longer-term simulations of plume development. Reprocessing of the 2004 dataset to match the earlier surveys will be carried out in the near future and further repeat surveys are planned. Results will be incorporated into this ongoing study as they become available.

Acknowledgements
The authors thank the CO2STORE consortium for permission to publish this work. CO2STORE is funded by the EU Thermie Programme, by industry partners Statoil, BP, ExxonMobil, Norsk Hydro, TotalFinaElf, Vattenfall, Schlumberger, and by national governments. R&D partners are BGR (Bundesanstalt fur Geowissenschaften und Rohstoffe), BGS (British Geological Survey), BRGM (Bureau de Recherches Geologiques et Minieres), GEUS (Geological Survey of Denmark), IFP (Institute Francais du Petrole), TNO (Netherlands Institute of Applied Geoscience – National Geological Survey) and SINTEF Petroleum Research. Chadwick, Noy and Williams publish with permission of the Executive Director, BGS (NERC).

List Of References
[1] Zweigel P, Arts R, Lothe AE, Lindeberg E. Reservoir geology of the Utsira Formation at the first industrial-scale underground CO_2 storage site (Sleipner area, North Sea). In: Baines S, Gale J, Worden RH, editors. Geological Storage for CO_2 Emissions Reduction. Special Publication of the Geological Society, London; 2004, p. 165 – 180.

[2] Chadwick RA, Arts R, Eiken O, Kirby GA, Lindeberg E, Zweigel P. 4D seismic imaging of a CO_2 bubble at the Sleipner Field, central North Sea. In: Davies RJ, Cartwright JA, Stewart SA, Lappin M, Underhill JR, editors. 3-D Seismic Technology: Application to the Exploration of Sedimentary Basins. Geological Society, London; 2004, p. 311-320.

[3] Chadwick RA, Arts R, Eiken O. 4D seismic quantification of a CO_2 plume at Sleipner, North Sea. In: Dore AG, Vining BA, editors. Petroleum Geology: North-West Europe and Global Perspectives. The Geological Society, London; 2005, p. 1385 – 1399.

[4] Arts R, Eiken O, Chadwick RA, Zweigel P, Van der Meer L, Zinszner B. Monitoring of CO_2 injected at Sleipner using time lapse seismic data. In: Gale J, Kaya Y, editors. Greenhouse Gas Control Technologies. Elsevier Science Ltd, Oxford; 2003, p. 347 – 52.

[5] Johnson JW, Nitao JJ. Reactive transport modelling of geologic CO_2 sequestration at Sleipner. In: Gale J, Kaya Y, editors. Greenhouse Gas Control Technologies. Elsevier Science Ltd, Oxford; 2003, p. 327 – 332.

[6] Gaus I, Azaroual M, Czernichowski-Lauriol I. Reactive transport modelling of the impact of CO_2 injection on the clayey cap rock at Sleipner (North Sea). Chem. Geol. 2005; 217: 319-37.