Chapter 10: Offshore CO_2 Storage: Sleipner natural gas field beneath the North Sea

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Abstract

Sleipner is the world's longest-running industrial-scale storage project and so far the only example of underground CO_2 storage arising as a direct response to environmental legislation. It commenced in 1996, injecting around one million (1Mt) of CO_2 per year into the Utsira Sand, a relatively shallow saline aquifer. By late 2011 over 13Mt of CO_2 had been securely stored. A comprehensive research-focussed monitoring programme has been carried out with multiple time-lapse surveys; predominantly 3D seismic but also 2D seismic, gravimetry and controlled source electromagnetics (CSEM). The time-lapse seismic data image the CO_2 plume clearly in the reservoir with very high detection capability and show no evidence of CO_2 migration from the storage reservoir into the overburden. Although not specifically designed for this purpose, the monitoring programme fulfills most of the requirements of the recently developed European regulatory framework for CO_2 underground storage.

10.1 Introduction

Sleipner, situated in the Norwegian sector of the North Sea, is the world's longest-running industrial-scale storage project (Baklid et al. 1996). This chapter firstly sets out the background and rationale for the CO_2 storage operation. It then outlines the geological setting including key reservoir and overburden properties. The aims of the monitoring programme are explained and key monitoring results described. Finally the monitoring is placed in the context of recently developed European storage legislation, with emphasis on key regulatory requirements such as predictive modeling and verification and leakage detection.

10.2 Background

CO_2 injection at Sleipner commenced in 1996. Natural gas produced from a depth of around 3400 to 3600m in the Sleipner Vest gas field contains about 9 % CO_2. This has to be reduced to less than 2.5 % for the gas to meet saleable specification, so the CO_2 is separated at the Sleipner T platform via amine scrubbers. Prior to implementation of the Norwegian offshore carbon tax, the separated CO_2 would have been vented to the atmosphere, but in response to this legislation, the field operator Statoil and partners ExxonMobil and Total elected to develop the field with re-injection of the CO_2 into a large subsurface formation, the Utsira Sand. The whole injection and storage operation is cost-effective, with total tax avoided comfortably exceeding storage costs.

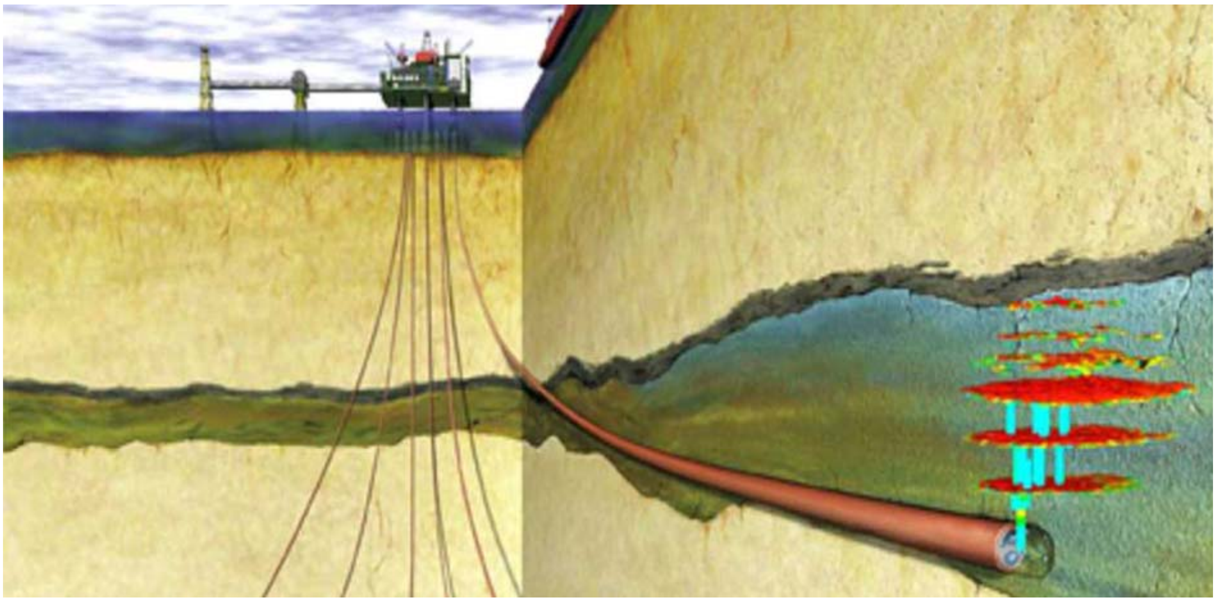

Figure 10.1 Schematic diagram of the Sleipner injection infrastructure and the CO_2 plume

The separated CO_2 contains 1 – 2% methane and is injected into the Utsira Sand, a regional-scale saline aquifer. Injection is via a single deviated well, sub-horizontal at the injection point which is located 1012 m below sea-level, some 200 m below the reservoir top (Fig. 10.1). Since 1996 CO_2 has been injected at a relatively uniform rate of around one million tonnes (Mt) per year, with about ten more years of gas production anticipated (Figure 10.2). By late 2011 over 13 Mt of CO_2 had been securely stored.

With this injection configuration, the wellbore lies beneath the buoyant CO_2 plume. This is important for two reasons. First, the wellbore is not impacted by the plume so does not constitute a containment risk. Second, no invasive monitoring or direct invasive measurement of the plume is possible (see below).

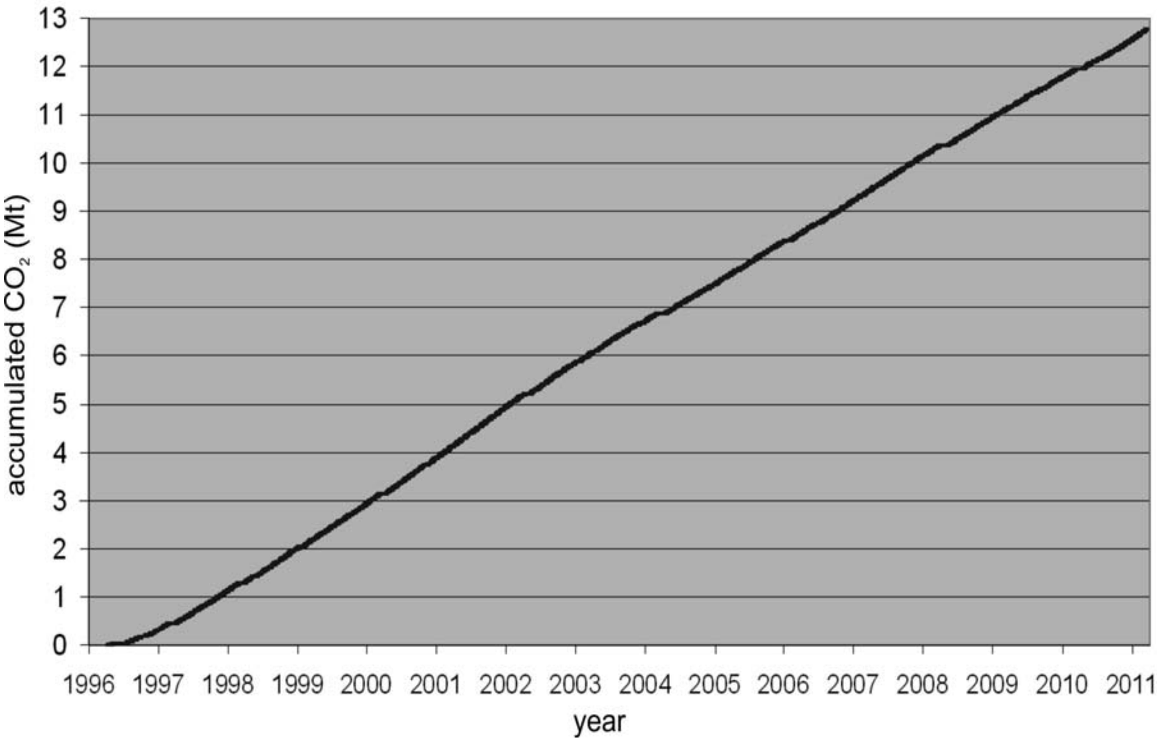

Figure 10.2 Sleipner CO_2 injection history 1996 to 2011.

10.3 Geological setting

The geological setting of Sleipner is relatively simple (e.g. Zweigel et al. 2004; Chadwick et al. 2004a) and a brief summary is given here.

10.3.1 Utsira reservoir

The Sleipner storage reservoir is the Utsira Sand, a saline aquifer of regional extent. It forms part of the late Cenozoic post-rift succession of the North Sea Basin and stretches for more than 400 km north to south and between 50 and 100 km east to west (Fig. 10.3a). Its eastern and western limits are defined by stratigraphical lap-out, to the southwest it passes laterally into finer-grained sediments, and to the north it occupies a narrow, deepening channel. Locally, particularly in the north, depositional patterns are quite complex with some isolated depocentres, and lesser areas of non-deposition within the main depocentre. The top Utsira Sand surface generally varies quite smoothly in the depth range 550 to 1500 m, and is around 800 – 900 m deep near Sleipner. Isopachs of the reservoir sand define two main depocentres (Fig. 10.3a), one in the south, around Sleipner, where thicknesses locally exceed 300 m, and another some 200 km to the north with thicknesses approaching 200 m.

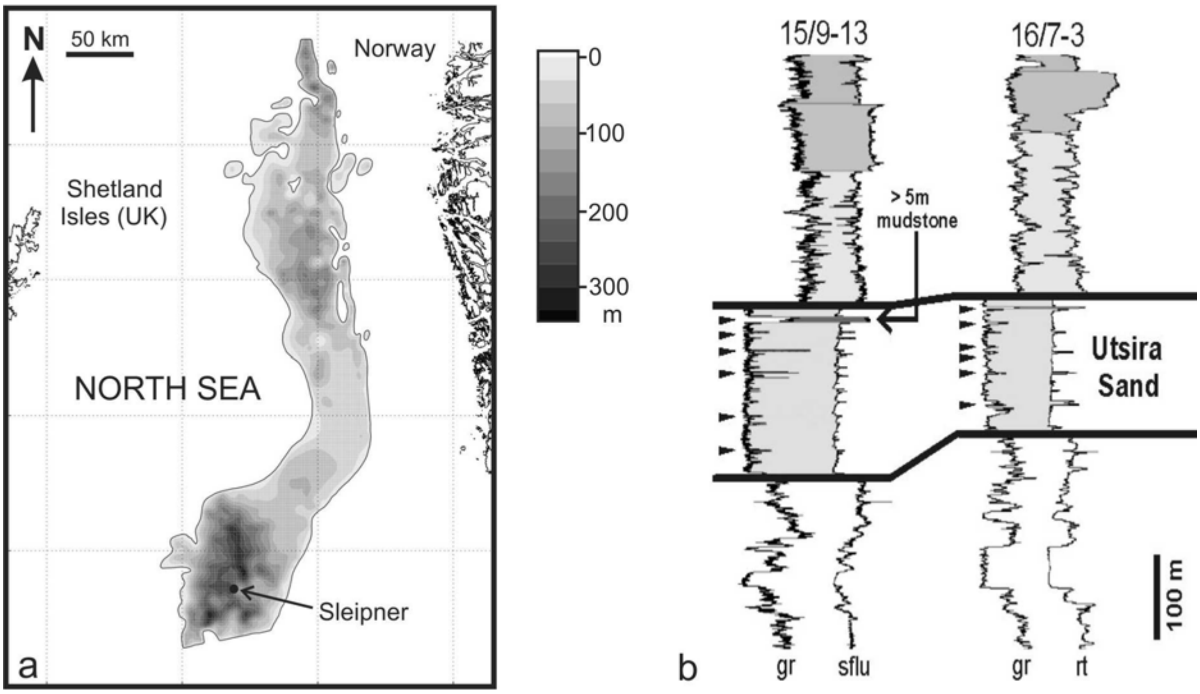

Figure 10.3 a) Thickness map of the Utsira Sand showing the location of Sleipner b) Sample wireline logs through the Utsira Sand from two wells in the Sleipner area. Note the low γ-ray signature of the Utsira Sand, with peaks denoting the intra-reservoir mudstones.

In the vicinity of Sleipner detailed reservoir structure has been mapped using 3D seismic data. The top of the Utsira Sand deepens generally to the south, but in detail it is gently undulatary with small domes and valleys. The CO_2 injection point is located beneath a small domal feature that rises about 12 m above the surrounding topseal topography. The base of the Utsira Sand is structurally more complex, and is characterised by the presence of numerous mounds, interpreted as mud diapirs. These are commonly about 100 m high and are mapped as isolated, circular domes typically 1 – 2 km in diameter, or irregular, elongate bodies with varying orientations, up to 10 km long. The mud diapirism is associated with local faulting that cuts the base of the Utsira Sand, but does not appear to affect the upper parts of the reservoir or its caprock (Zweigel et al. 2004). Significant faulting with a structural origin is absent.

Internally the Utsira Sand comprises stacked overlapping ‘mounds’ of very low relief, interpreted as individual fan-lobes and commonly separated by thin intra-reservoir mudstone beds. The depositional environment is uncertain; many believe that this is a turbiditic sand, deposited in moderately deep water (Gregerson et al. 1997) but a shallow shelf setting has also been proposed.

On wireline logs the Utsira Sand characteristically shows a sharp top and base (Fig. 10.3b), with the proportion of clean sand in the reservoir unit typically above 70%. The non-sand fraction corresponds mostly to the thin mudstones (typically about 1m thick), which show as peaks on the gamma-ray and resistivity logs. In the Sleipner area, a thicker, laterally persistent bed, the ‘five-metre mudstone’, separates the uppermost sand unit from the main reservoir beneath (Fig. 10.3b). The mudstone layers constitute important permeability barriers within the reservoir sand, and have proved to have a significant effect on CO_2 migration through the reservoir (Arts et el. 2004).

Core samples and drill cuttings show the Utsira Sand to be mostly fine-grained and largely uncemented. Porosity estimates from core, based on microscopy and laboratory experiments, are in the range 27% to 42% and regional porosity estimates from wireline logs are in the range 35 to 40%. Permeabilities are correspondingly high with measured values (from both cores and water-production testing) ranging from around 1 to 8 Darcy.

There are no downhole temperature measurements at Sleipner, but large-scale water production from the Utsira Sand at the nearby Volve field (~8 km distant) yields reliable reservoir temperatures. Here, 3 - 4 Mt of water per year are produced for pressure support in the Volve field (Utsira water has much lower sulphate content than seawater and so is used to reduce the risks of scaling in the production wells after water breakthrough). Before water production started, the Volve well was shut-in for 50 days, and a temperature reading of 27.4 - 27.7 ^{o}C at 768 m below sea-level was made. A consistent Utsira water temperature of 32.2 °C was obtained during flow, with a perforation interval of 822 to 1009 m but unknown inflow profile from the reservoir. Projecting these values on a vertical profile gives a linearized relationship $T(z) = 31.7z + 3.4$ (+/- 0.5^{o}C) (Alnes et al. 2011). Applying this to the Sleipner injection area gives initial temperatures of about 29 ^{o}C at the reservoir top and 35.5 ^{o}C at the depth of injection (1012m).

10.3.2 Overburden

The overburden of the Utsira reservoir around Sleipner is about seven hundred metres thick. The primary reservoir caprock comprise a basin-restricted mudstone some 50 to 100 m thick, extending more than 50 km west and 40 km east of the area currently occupied by the CO_2 injected at Sleipner and well beyond the predicted final migration footprint of the plume (Zweigel et al. 2001). Above this, prograding sediment wedges of late Pliocene age are dominantly muddy in the basin centre, but coarsen into a sandier facies both upwards and towards the basin margins. The shallower overburden is of Quaternary age, mostly glacio-marine clays and glacial tills.

Seismic, wireline log and cuttings data enable many overburden properties to be characterized and mapped on a broad scale. Cuttings samples from wells in the vicinity of Sleipner comprise dominantly grey clay silts or silty clays, classified as non-organic mudshales and mudstones (Krushin 1997). XRD-determined quartz contents suggest displacement pore throat diameters in the range 14 to 40 nm, consistent with capillary entry pressures of between about 2 and 5.5 MPa (Krushin 1997). In addition, the predominant clay fabric with limited grain support indicates an effective seal of the type capable of supporting a column of 35º API oil greater than 150 m in height (Sneider et al. 1997).

A core sample was obtained from the caprock in 2002 (Fig. 10.4). The core material is typically a grey to dark grey silty mudstone, uncemented and quite plastic, and generally homogeneous with only weak indications of bedding. It contains occasional mica flakes, individual rock grains up to three mm in diameter and a few shell fragments. XRD-determined quartz contents suggest displacement pore throat diameters in the range 2.2 to 21 nm (Kemp et al. 2002), similar values to those of the cuttings samples from other wells, and suggesting capillary entry pressures to dense phase CO_2 ranging from 3.4 to 37 MPa .

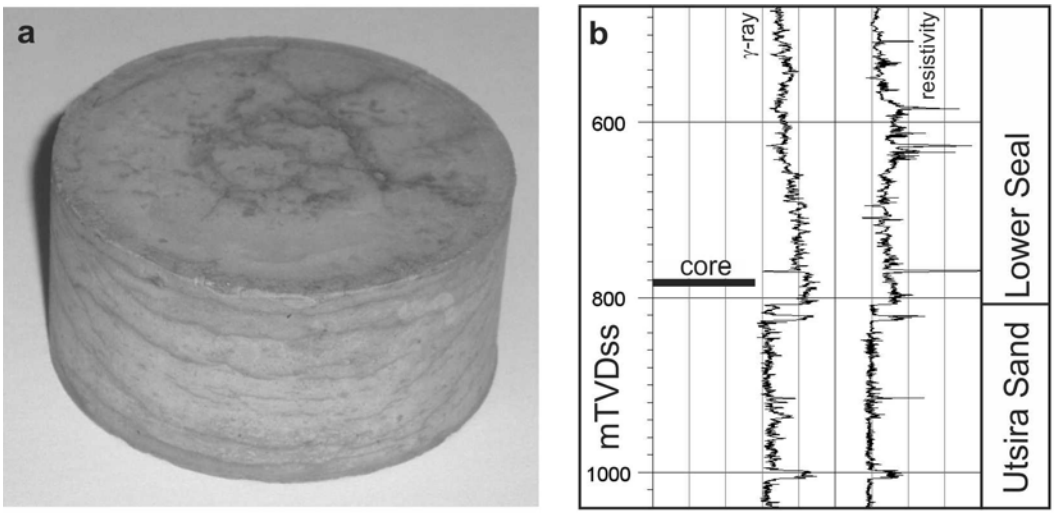

Figure 10.4 a) Caprock core from Sleipner b) Wireline logs from the cored well showing core position

The core has been subjected to a number of laboratory procedures including geomechanical and flow transport testing. Long-term hydraulic and nitrogen gas transport testing (Harrington et al. 2010) on the caprock core at reservoir P,T conditions, indicates porosities in the range 32% to 38%, intrinsic permeabilities ranging from 4×10^{-19} m^2 (~4×10^{-7} Darcy) vertical to 1×10^{-18} m^2 (~10^{-6} Darcy) horizontal, and a capillary entry pressure to nitrogen of around 3 MPa. A parallel study (Springer et al. 2005) showed *in situ* porosity of ~35% and vertical intrinsic permeability in the range 7.5 - 15 x 10^{-19} m^2 (7.5 – 15 x10^{-7} Darcy), slightly higher than found by Harrington et al. (2010), but consistent with a lower clay content in the samples used in the second study. Capillary entry pressure was 3 - 3.5 MPa to both nitrogen and gaseous CO_2, and ~1.7 MPa to supercritical CO_2.

Induced adverse geomechanical effects on topseal integrity are unlikely. Injection overpressures seem to be very small (Chadwick et al. 2012) and insufficient to induce either dilation of incipient fractures or microseismicity (Zweigel and Heill 2003).

10.3.3 Thermal structure of the CO_2 plume

The CO_2 at Sleipner is injected in a dense phase. At the wellhead, temperature is thermostatically controlled to 25 ^oC and pressures have been measured at between 6.2 and 6.6 MPa. No downhole measurements are taken, but bottom-hole conditions can be estimated by solving the flow equations along the well. By assuming hydrostatic pressure (10.5 MPa) at the injection point, the corresponding temperature of the CO_2 stream is estimated at 48 ^oC at the bottom of the hole. If reservoir pressure were to build up during injection, the temperature would rise, at about 1 ^oC per MPa, causing the gas/fluid ratio in the wellbore to change and buffering any pressure increase at the wellhead.

In the reservoir, most of the injected CO_2 will be cooled down to the ambient reservoir temperature. However, with time a temperature perturbation will have developed, with the core part of the CO_2 plume gradually warming. Adiabatic expansion of CO_2 from the injection point up to top reservoir would give a CO_2 temperature of 36.6 ^oC at the topseal. Such warm

CO_2 would have a density of about 485 kgm^{-3} at the injection point, and about 425 kgm^{-3} at the reservoir top.

A rough estimate of the temperature distribution within the CO_2 plume can be obtained by assuming the temperature front is sharp (i.e. that the CO_2 and the rock matrix is either at initial reservoir temperature or at the higher temperature set by the injected CO_2). With a simple assumption of a cylindrical high-temperature region spanning the entire height of the CO_2 plume, a constant fraction of 7% of the CO_2 will be in the high-temperature state (Alnes et al. 2011). Densities of 'cold' CO_2 will be about 710 kg/m^3 at top reservoir and fairly similar at larger depths, and the warmer 'core' will then have considerably lower density and correspondingly higher buoyancy.

10.4 Monitoring Programme

A varied time-lapse monitoring programme has been carried out at Sleipner. Its aims are twofold: first and foremost to track storage performance and assure continued storage integrity; secondly, via a number of scientific research projects, to test and refine monitoring tools and to improve understanding of CO_2 migration and trapping mechanisms in the storage reservoir.

The monitoring is all non-invasive with a strong emphasis on deep-focussed methods (Table 10.1). The very high time-lapse monitoring frequency for some of the tools (notably 3D surface seismic) reflects this large research element. Basic operational monitoring requirements for Sleipner would be much more limited.

Table 10.1 Monitoring at Sleipner

	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
3D surface seismic	✓					✓		✓	✓		✓		✓		✓	
2D surface seismic (hi-res)													✓			
Seabed imaging (ss sonar, multibeam)													✓			
Seabed gravity									✓			✓				✓
CSEM															✓	
Wellhead pressure			continuous													
Cumulative CO_2 injected at TL surveys (Mt)	0.00		injection starts			2.35		4.25	4.97(s) 5.19(g)		6.84	7.74	8.40		10.15 (s) 10.38 (em)	11.05

A number of key risks were identified prior to injection and the monitoring programme was designed to address these:

Migration through the caprock seal into the overburden: Migration through intact rocks is considered to be very unlikely given the high capillary entry pressures of water-saturated caprock strata (see above) and the lack of significant faulting. Monitoring strategy is to use the 4D seismic to track CO_2 migration in the reservoir and monitor for any changes in the overburden.

Migration into wellbores resulting in potential leak pathways to the seabed: This is considered unlikely in the short-term due to the topography of the topseal which tends to keep the buoyantly trapped CO_2 away from the closer wells. The risk management strategy is to make predictive models of lateral spread of CO_2 with time and use 4D seismic to track CO_2 migration in the reservoir to identify developing situations with respect to the wells.

Migration of CO_2 outside of the Sleipner licence area: In the longer-term this could impact on third party wellbores and may also compromise future external activities (such as by making drilling through the Utsira reservoir more costly, or by blanking seismic signals beneath the plume). The risk management strategy is similar to the above, using predictive modelling and 4D seismic to track CO_2 migration in the reservoir to identify developing situations with respect to the licence boundary.

Generic public relations issues: Imperfect understanding of storage could result in inaccurate or poorly informed criticism of the project from external parties. The role of monitoring is to track site performance to demonstrate with a high degree of confidence what is happening in the subsurface and how storage processes are understood.

The monitoring programme at Sleipner is generally perceived to be a great success and is commonly cited as a good example of how to monitor an industrial-scale storage site. The key monitoring tool is 4D seismic which has proved spectacularly effective in tracking the plume, but other techniques have also been tested with varying degrees of success.

10.4.1 4D seismic

<u>Imaging in the reservoir</u>
Time-lapse surface 3D seismic surveys have been acquired in 1994 (baseline), 1999, 2001, 2002, 2004, 2006, 2008 and 2010. Details of the CO_2 distribution in the reservoir are clearly evident (Fig. 10.5). In cross-section the CO_2 plume is seen to be roughly 200 m high and imaged as a number of bright sub-horizontal reflections within the reservoir, growing with time. These are interpreted as tuned wavelets arising from thin (mostly < 8 m thick) layers of CO_2 trapped beneath the intra-reservoir mudstones and the reservoir caprock. The plume is elliptical in plan, with a major axis increasing to about 4500 m by 2010, accompanied by development of a prominent northerly extension since 2004. A strong velocity ‘pushdown’ is evident on reflectors beneath the plume and a vertical column of markedly reduced reflectivity, up to 80 m in diameter, forms a ‘seismic chimney’ roughly above the injection point (Chadwick et al. 2004b).

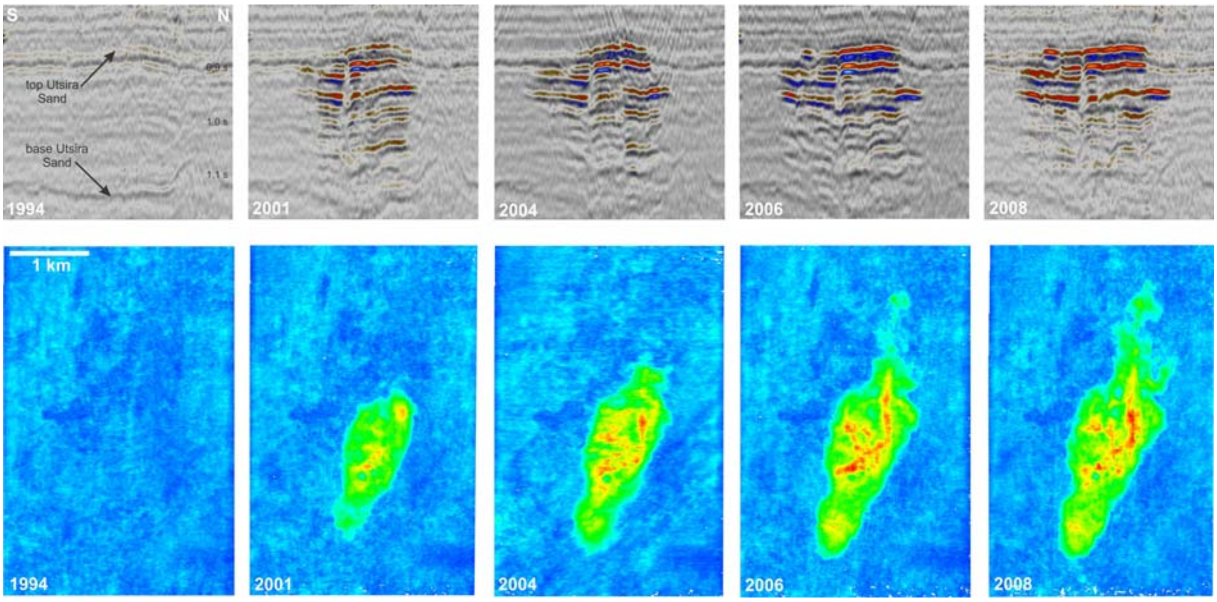

Figure 10.5 Time-lapse images of the CO_2 plume at Sleipner a) N-S inline through the plume b) map of total plume reflectivity. Note the strong velocity pushdown of reflectors beneath the plume and a vertical 'chimney' of reduced reflectivity prominent on the inline.

<u>Out of reservoir migration</u>

In addition to imaging the CO_2 plume within the reservoir, a key objective of the time-lapse seismic is to indicate whether any detectable migration of CO_2 into the caprock / overburden has occurred (in other words, whether CO_2 is being contained within the primary reservoir). The most straightforward way of assessing this is to use difference datasets, obtained by subtracting the baseline dataset from a repeat dataset, to reveal whether any systematic changes have occurred that may be indicative of CO_2 migration. Examples of difference time-slices in the overburden succession (Fig. 10.6) typically show a rather random difference signal with a characteristic mottled appearance. This difference signal, termed repeatability noise, is due to unavoidable mismatches between the baseline and the repeat survey.

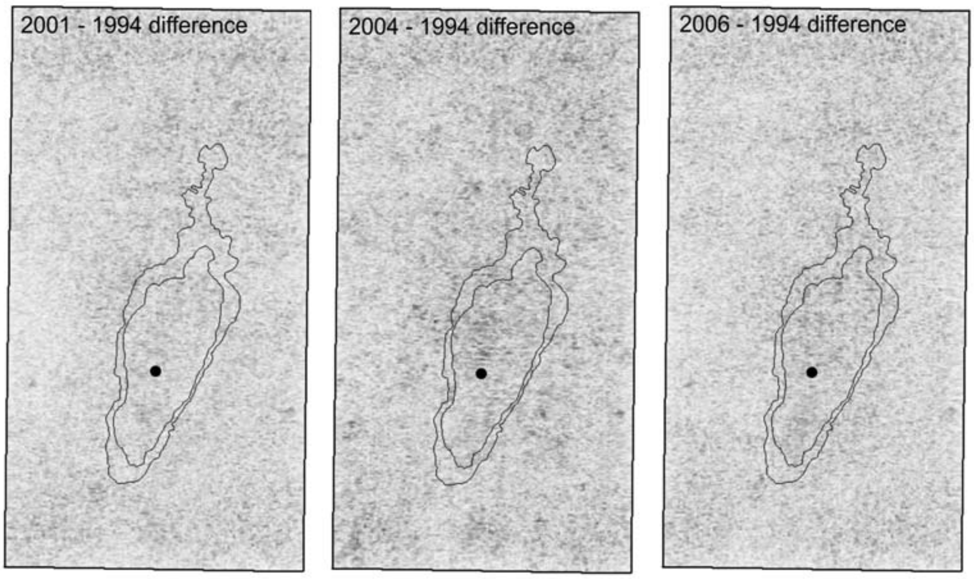

Figure 10.6. Time-slice maps through successive difference cubes, located in the overburden immediately above the Utsira reservoir. The mottled signal is composed of repeatability noise

which shows no systematic correlation with the spatial footprint of the CO_2 plume (black polygons show the expanding outline of the plume from 2001 to 2006). The 2004 survey was acquired with ship lines perpendicular to the other surveys, acquisition geometries are completely different and the intrinsic mismatch is higher with more repeatability noise. Spot denotes position of injection point.

Detection of CO_2 depends on being able to discriminate between the repeatability noise and real time-lapse changes due to CO_2. It has been estimated that the Sleipner datasets can detect accumulations of CO_2 as small as 4000 m^3 (Chadwick 2010). This corresponds to about 2800 tonnes at the top of the reservoir but progressively less at shallower depths as CO_2 density decreases. The key strength of 3D seismic is the continuous and uniform coverage of the storage footprint, so the detection limit is robustly maintained across the survey area.

Predictive model calibration and verification

Early Sleipner work concentrated on history-matching flow simulations of whole plume development with the observed datasets (e.g. Van der Meer et al. 2001; Lindeberg and Bergmo 2003). A general match of plume development and flow simulations is readily obtainable, but a key uncertainty remains; that of how the CO_2 is transported through the intra-reservoir mudstones. One group of models assumes that the mudstones are semi-permeable, another group of models assumes that they are impermeable but with holes. Both groups of models are capable of reproducing the general morphology and rate of development of the plume.

For longer-term performance prediction the development of the upper plume is most relevant, in particular the topmost layer of CO_2 trapped directly beneath the caprock (Chadwick and Noy 2010). The lateral spread of this topmost layer (Fig. 10.7) is very clearly imaged on the 4D seismic and shows clear evidence of the buoyant infilling of top reservoir topography by the CO_2. Particularly prominent is a north-trending linear ridge in the topseal surface, along which the CO_2 front has advanced at a rate of about 1m per day (Fig. 10.7).

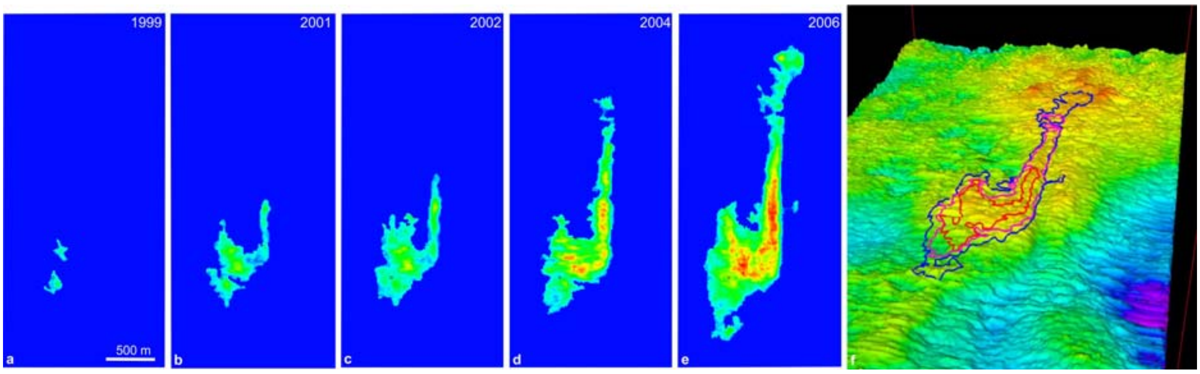

Figure 10.7 Growth of the topmost CO_2 layer at Sleipner a) – e) plan views of the layer spreading from 1999 to 2006. Perspective view of the topography of the top reservoir, showing the CO_2 – water contacts in 2001 (red), 2004 (purple) and 2006 (blue). Note the north-trending tongue of CO_2 corresponding to spilling along a linear topographic ridge.

Detailed quantitative analysis of the layer has been used to develop numerical flow simulations to history-match with the observed seismic (Fig. 10.8). There are significant issues with the history-matching, most notably the difficulty in modelling the very rapid northward migration of the plume between 2001 and 2006. The models shown here use lower densities and viscosities for the CO_2 than would be expected for pure CO_2 at ambient reservoir temperature. This might be explained by the central core of warmer CO_2 discussed above, perhaps ‘fast-tracking’ to the reservoir top, or by preferential accumulation of the minor, less dense, methane component at the reservoir top. Both would have the effect of significantly increasing the mobility of the plume fluid. Setting aside the uncertainties in CO_2 properties, the spatial mismatches are mostly quite small and are most likely caused by small errors in the depth imaging of the reservoir top topography (Chadwick and Noy 2010).

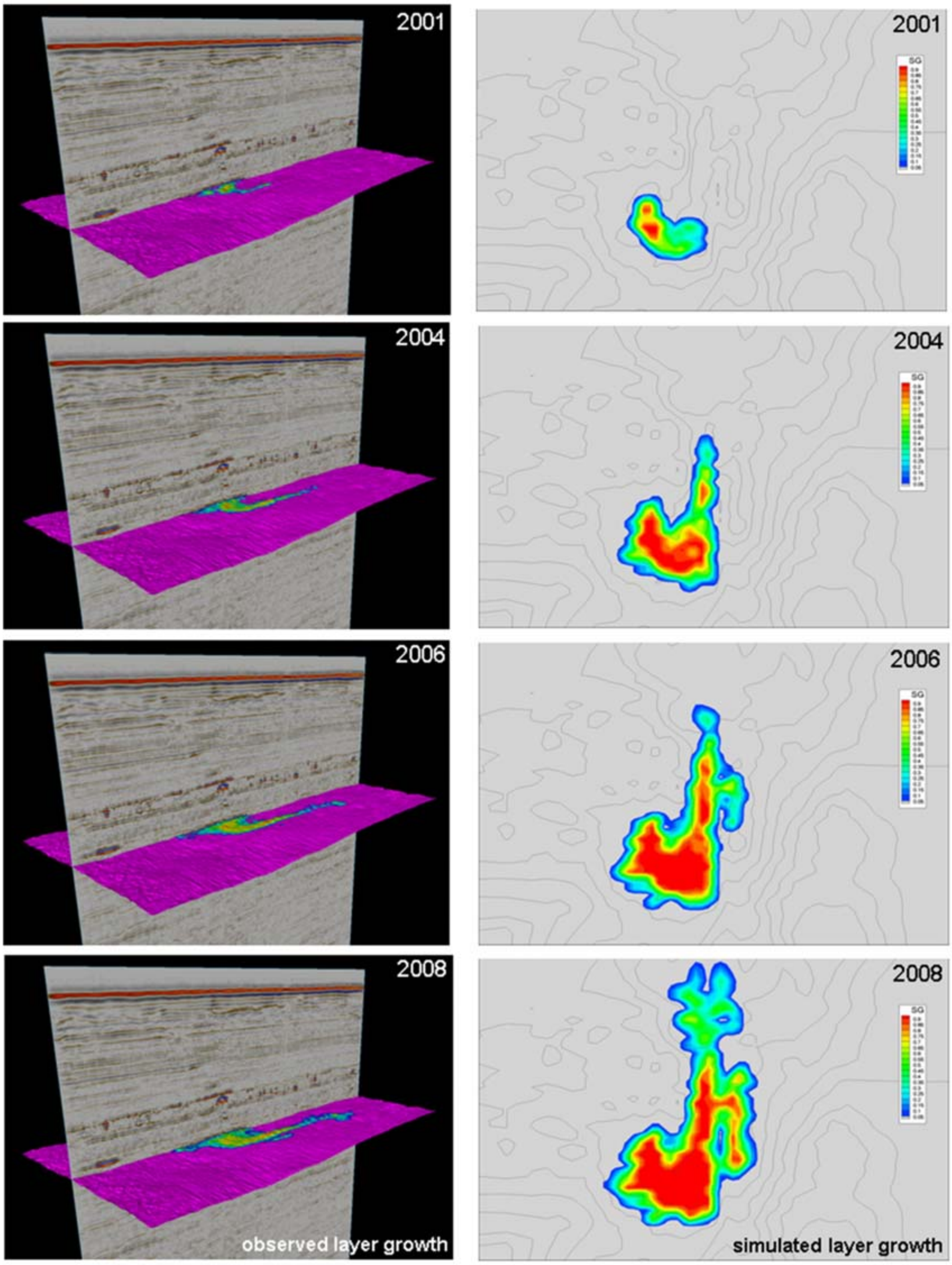

Figure 10.8 Topmost CO_2 layer in 2006 showing observed images in perspective view (left) and flow simulations using variable reservoir flow parameters in plan view (right).

Quantification
A significant amount of work has focussed on quantitative analysis of the Sleipner datasets. Early papers concentrated on quantification of the plume reflectivity and velocity pushdown with the aim of independently verifying the measured injected amount of CO_2 (Arts et al. 2004; Chadwick et al. 2004b; 2005). A satisfactory match was obtained for the 1999 dataset, using a saturation model containing around 85% of the known injected CO_2 whilst maintaining a satisfactory match with the seismic data. On the other hand, significant volumes of low saturation CO_2 were required in the model which is difficult to reconcile with our understanding of multi-phase flow in the reservoir where low saturation CO_2 is expected to be virtually immobile.

Significant uncertainties render a unique verification very challenging however, and it appears that the more recent Sleipner datasets are becoming more difficult to model. With time, reflectivity in the deeper plume is fading and velocity pushdown is becoming more difficult to map (Fig. 10.5a). These are partly seismic imaging effects arising from generally increasing CO_2 saturations within the plume envelope, but may also signify real and significant changes in CO_2 distribution in the deeper part of the plume.

Nevertheless some simple quantitative parameters can be measured and correlated with the injection history. Velocity pushdown time delays can be integrated over the whole spatial footprint of the plume, and reflection amplitudes can be summed for all layers. These are straightforward quantitative measures, which can be plotted against injected mass (Fig. 10.9). Both show a remarkably linear relationship. This is surprising given the probable non-linear velocity-saturation relationship from rock physics, the non-linear thickness-amplitude relationship arising from thin-layer tuning and attenuation shadowing of deeper layers. Some of these effects may counteract each other; certainly there appears to be a robust empirical relationship between the gross seismic response of the plume and the injection history.

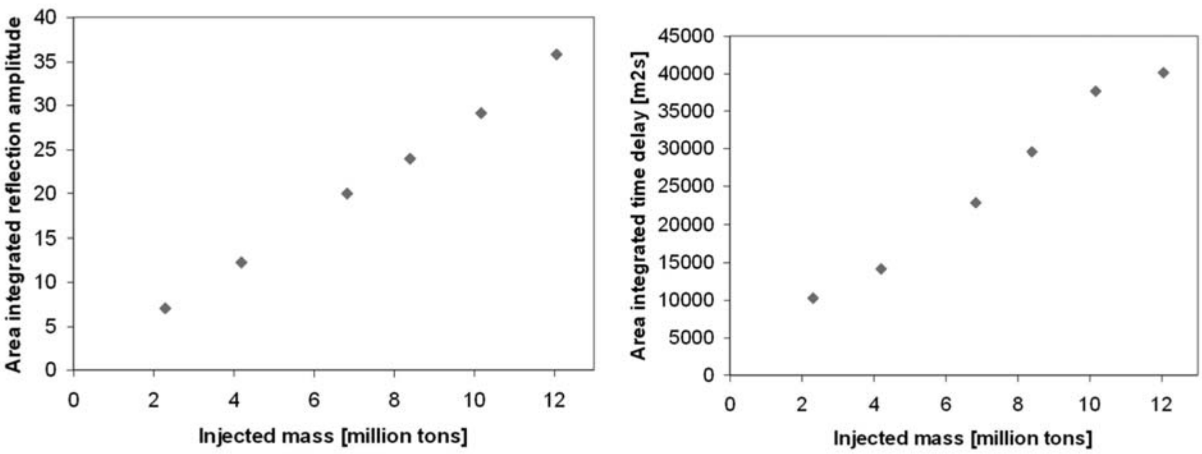

Figure 10.9 Reflection amplitudes for all layers (left), and area integrated pushdown (right), plotted against injected mass. Both measures show rather stable linearity with injection history.

In summary, it is clear that the 4D seismic clearly forms a powerful time-lapse monitoring tool capable of imaging the CO_2 plume to a high level of detail, monitoring for evidence of out-of-reservoir migration and constraining and verifying predictive models. The complete areal coverage is also a key element, meaning that all full and uniform spatial sampling of the reservoir and overburden is achieved.

10.4.2 Seabed gravimetry

An initial seabed gravity survey was acquired at Sleipner in 2002 with 5.19 Mt of CO_2 injected. Repeat surveys were then acquired in 2005 and 2009 with 7.74 Mt and 11.05 Mt of CO_2 injected respectively. The surveys used pre-positioned concrete benchmarks on the seafloor (see below) that served as reference locations for the (repeated) gravity measurements. Relative gravity and water pressure readings were taken at each benchmark by a customised gravimetry and pressure measurement module mounted on a Remotely Operated Vehicle (Fig. 10.10a). Benchmarks were deployed in two perpendicular lines overlapping the subsurface footprint of the CO_2 plume (Fig. 10.10b), additional stations being added in 2009 to allow for the increased plume area. Each benchmark was visited at least three times to better constrain instrument drift and other errors, resulting in a single station repeatability of about 2 to 4 µGal. For time-lapse measurements an additional uncertainty of associated with the relative measurements (arbitrary reference null level). Depending on which parameter to invert for, the final detection threshold for Sleipner ranges from less than 1 µGal (single parameter inversion) to 5 µGal (single station detection).

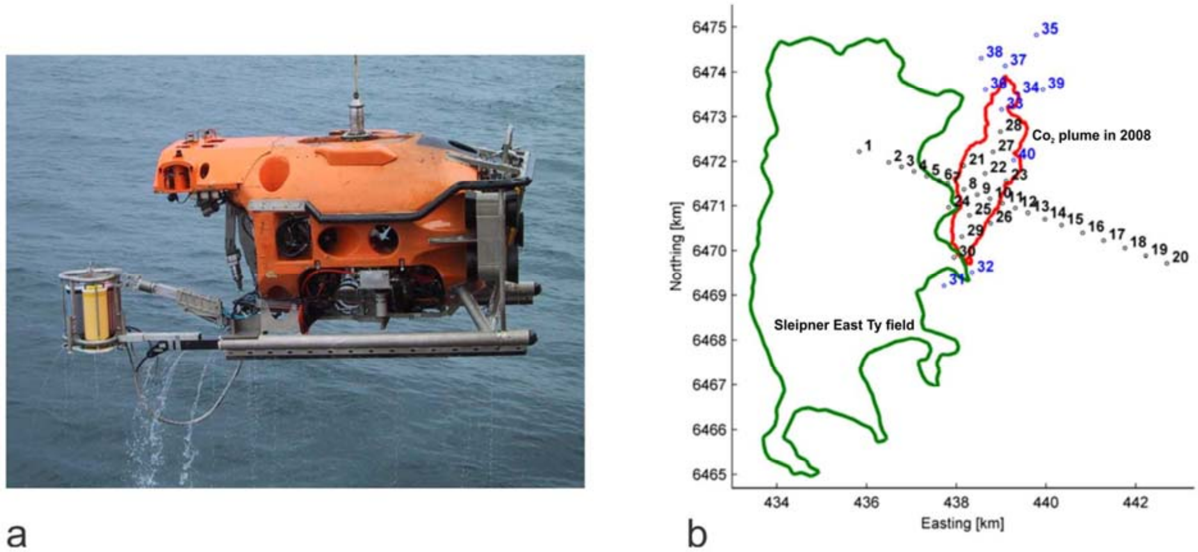

Figure 10.10 a) ROV and seabed gravimeter deployed at Sleipner b) location of the seabed benchmarks with respect to the 2008 CO_2 plume footprint.

The gravimetric response of the additional CO_2 was obtained by calculating the time-lapse response from the Sleipner East field (the deeper gas reservoir currently in production) and removing this from the measured gravity changes since 2002. The first gravity analysis focussed on constraining the *in situ* density of CO_2. Initial modelling of the 2005 dataset (Nooner et al. 2006) concluded that the average CO_2 density in the plume was about 530 kgm^{-3}. One accuracy issue concerns the benchmarks which have experienced vertical movements of up to 15 cm relative to each other between the surveys. These could be caused by enhanced seafloor erosion or fish digging and sheltering beneath the benchmarks (as has been observed during measurement campaigns). More recent modelling, based on optimising several parameters simultaneously and with improved application of the various data corrections, including the changing benchmark elevations (Alnes et al. 2008), gave a CO_2 density of about 760 kgm^{-3}.

The 2009 dataset, corresponding to a greater incremental mass of CO_2, should be more reliable and Alnes et al. (2011) obtained a best-fit CO_2 density of 720 ± 80 kgm^{-3}. These figures can be compared with the average CO_2 density in the plume as calculated from temperature considerations. With a warm core of the plume constituting 7% of the mass (as described above), calculated average density may reduce from about 705 kg/m^3 to about 675 ± 20 kgm^{-3} (Alnes et al. 2011). This can be compared with the gravity-based estimates of density, and any discrepancy may be attributed to the amount of CO_2 dissolved. When CO_2 dissolves into the formation brine it loses most of its gravitational effect, so models which assume that all CO_2 is still in the free phase will tend to overestimate the true density. Neglecting small changes in brine density that occur when CO_2 dissolves, the dissolution effect is given by:

$$\rho_{grav} = \rho_{actual} (1/1- \alpha)$$

where α is the mass fraction of CO_2 dissolved.

Alnes et al. (2011) looked at the full range of uncertainty in terms of the gravity modelling and also in the thermal calculation of plume density, and concluded that the upper bound on total dissolution is 0.18 (18%), with a most likely figure significantly less than this. Flow simulations of the plume development suggest that dissolution values up to around 10% are quite likely, so the gravimetry data seems to be in reasonable accordance with this. It is clear that provided tight spatial constraints on plume location and shape are available from the seismic data, the gravity changes at Sleipner between 2002 and 2009 can provide quite robust information on apparent CO_2 densities within the plume and from this, estimates of dissolved CO_2.

10.4.3 Seabed imaging

Seabed imaging surveys (sidescan sonar, single beam and multibeam echosounding and pinger seabottom profiler) were acquired at Sleipner in 2006. A digital seabed bathymetry terrain model with 2m x 2m sampling was made from the multibeam echosounding (Fig. 10.11) showing the seafloor dipping gently from 80.8 m depth in the east to 83.0 m in the west. A mosaic was also composed from the sidescan sonar data (Fig. 10.12), which has higher resolution of seafloor features. Both mapping techniques were able to detect the six pipelines passing through the area, while the sidescan data also picked up the gravimetry benchmarks (about 1.5 m in diameter and 0.3 m in height). A number of linear features observed in the sidescan data are interpreted as anchor scars. No environmentally sensitive habitats have been identified, and no evidence of gas seepage was detected.

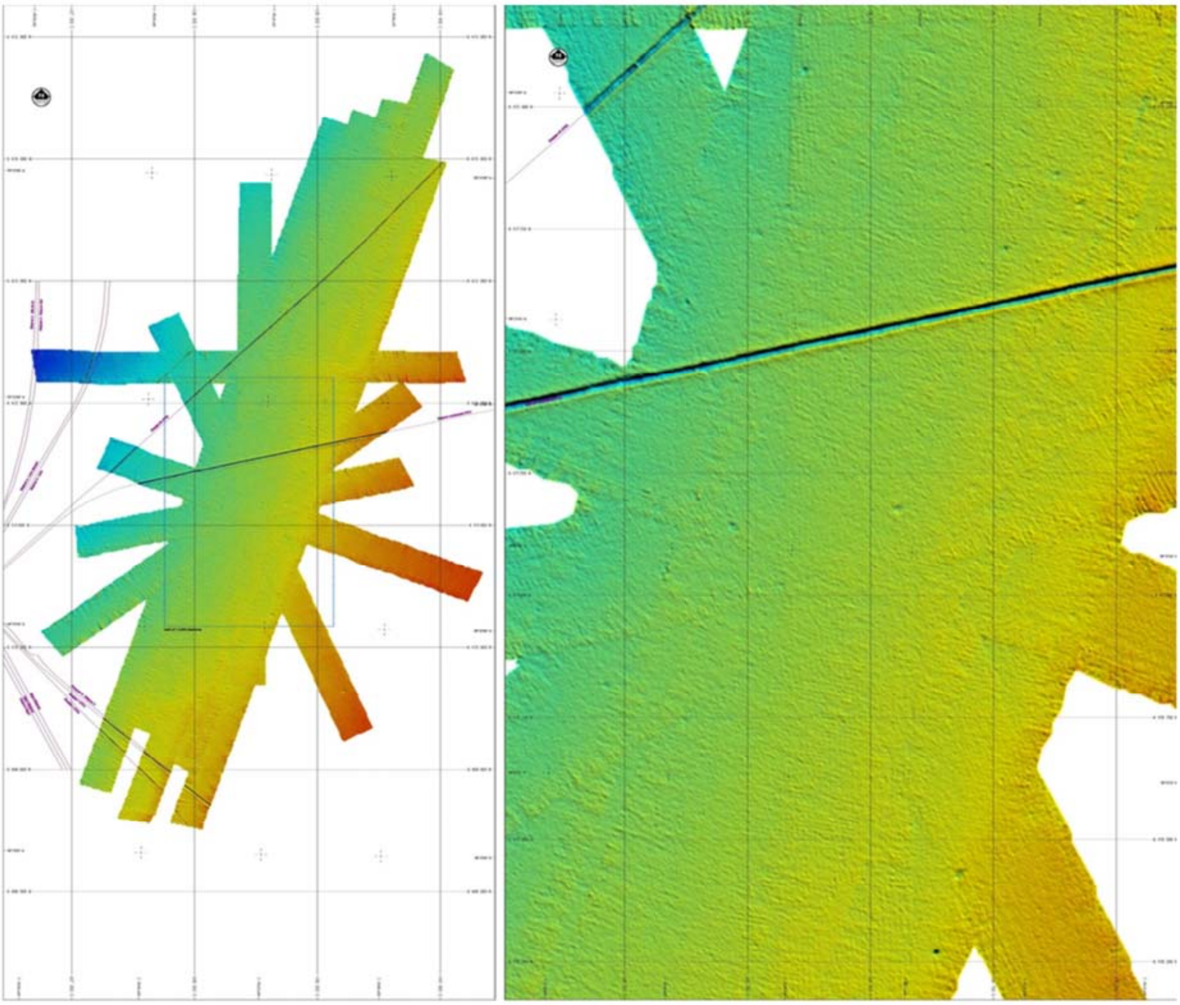

Figure 10.11 Multibeam echosounding image of the seafloor above Sleipner a) whole survey b) zooming in on the area above the injection point, showing small seabed features (note prominent linear pipelines).

10.4.5 Seabed ROV video

Comprehensive video footage has been taken from the remotely-operated vehicle (ROV) used to deploy the gravity meter (Fig. 10.12). In each of the 2002, 2005 and 2009 surveys the ROV transmitted from the seafloor continuously for a period of three to four days.

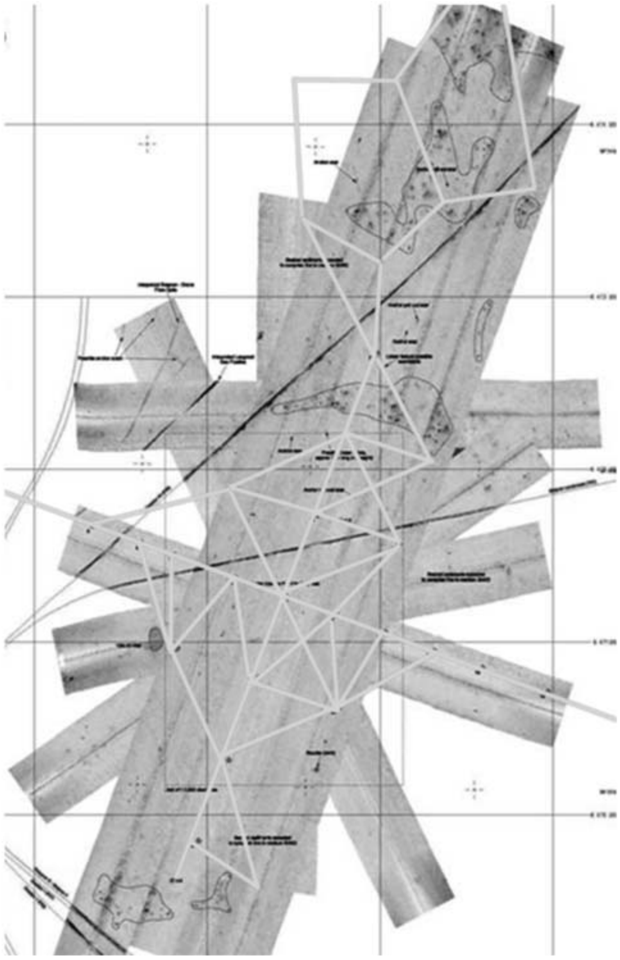

Figure 10.12 Sidescan sonar data with ROV (video) tracks in 2009 superimposed (green).

During the ROV survey, pilots maintained careful observation through the video cameras, and no seafloor bubble-streams were observed. Normal seabed conditions were encountered, with typical flora and fauna (Fig. 10.13). The data have not been analysed in systematic detail, but video records from 2009 have been stored for future availability.

Figure 10.13 Images extracted from the ROV video, showing a starfish and one of the concrete gravimetry benchmarks on the seabed.

10.4.6 Other surveys

Feasibility studies for Controlled Source Electromagnetic Sounding (CSEM) indicated that a resistivity anomaly should be detected from the Sleipner plume (Norman et al. 2008), so a trial CSEM line was acquired in September 2008. The profile aligns with the long axis of the CO_2 plume as mapped on seismic data (Fig. 10.14). The receiver line was 9.5 km long, with 20 receivers deployed at 20 different locations. Station spacing was 500 m, and in addition 7 locations had an extra receiver deployed 50 m away from the other. The source line was an extra 10 km to each side, and was towed two times with varying frequency spectra.

Analysis of the data has proved to be challenging. The shallow water depth gives strong air waves, and the nine pipelines crossing the survey profile further contaminate the data. It has been difficult to see clear anomalies from the plume area, however the latest results from a number of workers indicate there may be a detectable resistivity increase corresponding to the volume occupied by the plume. Analysis of these datasets is continuing.

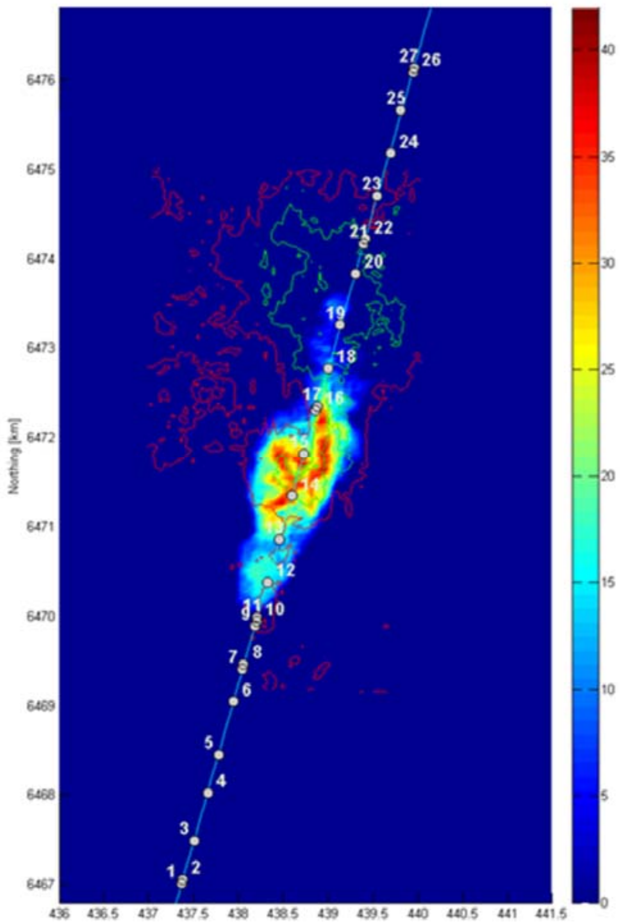

Figure 10.14: Map showing position of CSEM line and cumulative CO_2 plume layer thickness (m) estimated from seismic. Contours show top Utsira Sand at 792 and 800 m bsl.

In addition to the 3D seismic surveys discussed above, a high resolution 2D survey was acquired in 2006. This used a low-cost site survey vessel and results were very good. Improved resolution was obtained in the upper plume, at the expense of reduced signal penetration in the lower plume. Interpretation and analysis of the high resolution data is continuing.

A rather novel biomarkers study is also in progress. The object is to study the effects of higher than normal levels of CO_2 on marine invertebrates and the adaptations and mechanisms these animals possess to withstand the acidifying effects of CO_2 in water. The research in this project will involve exposing typical Sleipner crustaceans to elevated seawater/CO_2 levels and measuring changes in their ion regulating tissues by means of histochemistry, Western Blotting, PCR and enzyme activity analysis. The study has possible value for monitoring, in that changes in the seabed fauna may provide very early evidence of CO_2 leakage at seabed.

10.5 In context with the EU regulatory regime

Because Sleipner injection commenced in 1996 it is not covered by the recently developed European CCS regulations. It is nevertheless instructive to assess the extent to which the current monitoring programme meets the regulatory requirements.

There are three main elements to current storage regulation in Europe: the European Storage Directive, for offshore storage the OSPAR convention and the European Emissions Trading System (ETS). Sleipner can reasonably be placed in the context of all three.

10.5.1 OSPAR and the EC Storage Directive

The OSPAR Convention is concerned with protecting the marine environment in the NE Atlantic. A CCS amendment to OSPAR was published in June 2007 and is still in the process of ratification by partner nations. CCS requirements under OSPAR are focused around robust site selection and characterization; risk characterization and management, environmental exposure and impacts. Monitoring is a key OSPAR requirement. It should be carried out throughout a project, must be linked to the risk assessment and focus on specific issues including performance verification, leakage monitoring, monitoring local environmental impacts and demonstration of emissions reduction efficacy.

The European Directive on Storage was published in April 2009 and builds upon many of the OSPAR principles. Monitoring is a key requirement and is framed around enabling the operator to understand and to demonstrate understanding of current site processes, to identify any leakages and to predict future site behaviour. Further requirements of the monitoring include early identification of deviations from predicted site behaviour, provision of information needed to carry out remediation actions and the ability to progressively reduce uncertainty. In other words monitoring should effectively underpin the project risk management plan.

The current monitoring plan at Sleipner meets many of these objectives. In terms of understanding current site processes, explaining plume development is beset by some uncertainties, notably transport of CO_2 through the thin intra-reservoir mudstones, but in general terms the physics seems to be satisfactorily understood. Migration of the topmost CO_2 layers is crucial to predicting plume development in the medium term, in particular lateral migration of the plume in the upper reservoir. As discussed above, mismatches between observed and simulated behaviour are most likely down to small uncertainties in the geological model rather than to misinterpretation of the controlling processes (Fig. 10.8). This supports the contention that current site behaviour is, to all intents and purposes, well understood. This level of understanding further supports the reliability of longer-term predictive modeling. No systematic leakage monitoring is currently deployed at Sleipner. The current 3D seismic provides full and uniform volumetric coverage of the overburden, but the lack of observed changes, and the robust geological characterization of the caprock, taken together provide a strong case for no leakage. The seabed imaging surveys and underwater video further support this.

Perhaps the most challenging elements of the current regulations are the arrangements for site closure i.e. transfer of liability from the operator to the State.

The overall philosophy of the EU Directive is enshrined in the three minimum geological criteria for transfer of liability:

- Observed behaviour of the injected CO_2 is conformable with the modelled behaviour.
- No detectable leakage.
- Site is evolving towards a situation of long-term stability.

The first two bullets have been covered above. The requirement concerning demonstration of long-term stabilization is more challenging and depends almost exclusively on long-term predictive simulation of site behaviour. Post-injection monitoring will of course be a requirement and this can help to establish the path to long-term stabilization, but the ability of short-term monitoring to convincingly support such long-term forecasts will always be limited.

For Sleipner the key stabilization process is dissolution of free CO_2 into the reservoir pore-waters (summarized in Chadwick et al. 2008). The current non-invasive monitoring programme is unable to this process directly, as dissolved CO_2 is invisible on seismic. However the time-lapse gravimetry, as discussed above might be able to provide some constraints.

10.5.2 Emissions accounting under the EU ETS

The current monitoring system at Sleipner is not directed towards the requirements of emissions accounting which require some form of quantitative assessment of site leakage. In fact, even if Sleipner were operating under the European CCS regulations, there would not currently be a requirement for emission accounting as there is no evidence that the site might be leaking.

10.6 Commentary on future issues/trends

Sleipner provides a superb field-scale laboratory for the study of CO_2 storage in saline aquifers. So far we have witnessed sixteen years of uniform injection and have obtained detailed time-lapse images of the growing CO_2 plume. The research described here concentrates on an interpretative approach whereby detailed mapping of reflectivity and time-shifts in the CO_2 plume have been used to build detailed assessments of layer growth. These results have been history-matched against flow-simulations at a range of scales to understand more about flow and storage processes in the reservoir. More sophisticated seismic geophysics has also been deployed to determine elastic reservoir properties from the seismic signatures. In particular the pre-stack data have been analysed to see if additional information can be derived from the seismic raypaths at higher incidence angles. A number of approaches have been tried, mainly within the CO2ReMoVe project (www.co2remove.com). These include model-based pre- and post-stack inversion (Clochard et al. 2010), constrained AVO, common-focus-point imaging, spectral decomposition and velocity-attenuation tomography, and are summarised in Chadwick et al. (2010) and references therein. It is perhaps fair to say that the efficacy of many of these purely seismic techniques is limited by the strong thin-layer tuning effects which tend to swamp the more subtle reflectivity changes on both pre- and post-stack data. Recent work on attenuation and velocity dispersion (Rubino et al. 2011) has the potential to reveal some details on CO_2 distribution, and at what scales it mixes with the reservoir brine, providing the promise of improved quantitative analysis. Spectral decomposition and spectral inversion also show promise, whereby frequency tuning can provide additional constraints on CO_2 layer thicknesses. Work is ongoing in many of these areas.

The shallow monitoring programme at Sleipner is fairly rudimentary. Much more comprehensive shallow monitoring is likely to be a requirement for future storage sites, with a strong focus on acquiring robust baseline datasets. Main advances are likely to be in the field of emissions detection and measurement, both at the seabed and in the water column. Remotely-operated and autonomous underwater vehicles (ROVs and AUVs) are likely to play a key role in obtaining this type of detailed shallow-focussed data.

Looking further ahead, when injection at Sleipner finally ceases, there will be an opportunity for post-injection monitoring of an industrial-scale site. Such an invaluable opportunity should not be missed as it is likely that fundamental insights into post-injection plume development (e.g. spatial stabilization) will be gained. In the event that some form of monitoring (e.g. geophones, downhole gravimetry, fluid sampling) could be placed down the injection well (beneath the plume) it might also be possible to quantify key stabilisation processes such as dissolution.

Perhaps the key additional monitoring component which would significantly reduce many aspects of current uncertainty would be a monitoring well. In principle, a well through the plume could dramatically reduce quantitative uncertainty by providing a detailed vertical profile of CO_2 saturations in the plume. Sampling, possibly with core, might also cast light on flow mechanisms through the intra-reservoir mudstones. A major disadvantage of drilling such a well however would be that it might significantly reduce containment integrity, by puncturing the caprock (recall the current injection well is horizontally emplaced, beneath the CO_2 plume, so does not pose a containment risk). Another issue is that the full efficacy of a monitoring well cannot now be realised, since downhole baseline (pre-injection) measurements are no longer possible.

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