Ten years' experience of monitoring CO_2 injection in the Utsira Sand at Sleipner, offshore Norway

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Underground storage of carbon dioxide (CO_2) as a measure to reduce the amount of greenhouse gases in the atmosphere, and thereby to slow down global warming, has been studied and discussed widely over the last two decades (IPCC, 2005). Although considerable experience had been gained on CO_2 injection for enhanced oil recovery before the start of the Sleipner storage project, very little was known about the effectiveness of underground storage of CO_2 over very long periods of time. A number of demonstration sites have been initiated in the past few years, mainly for research purposes to investigate the feasibility of CO_2 injection in different types of reservoirs and to study the chemical and flow behaviour of CO_2 in the subsurface. The first, longest running and largest demonstration of CO_2 injection in an aquifer up to now is at Sleipner, in the central North Sea (Figure 1).

Since October 1996, Statoil and its Sleipner partners have injected CO_2 into a saline aquifer, the Utsira Sand, at a depth of 1012 m below sea level, some 200 m below the reservoir top. The CO_2 is separated on the platform from natural gas produced from the deeper lying Sleipner Gasfield and injected into the aquifer through a deviated well at a lateral distance of about 2.3 km from the platform (Figure 2).

This article outlines the experiences gained at this site, especially with respect to monitoring of CO_2 migration in the subsurface.

Utsira Sand reservoir

In the vicinity of Sleipner, the Utsira Sand is a highly porous (30-40%), very permeable (1-3 Darcy), weakly consolidated sandstone (Figure 3a), lying at depths between about 800 m and 1100 m, with a thickness of about 250 m around the injection site. Internally it comprises stacked overlapping 'leaves' or 'mounds' of very low relief, interpreted as individual fan-lobes and commonly separated by thin intra-reservoir mudstones. It is interpreted as a composite lowstand fan, deposited by mass flows in a marine environment with water depths of 100 m or more (Gregersen et al., 1997; Zweigel et al., 2004). The thin mudstones, in the order of 1 m thick, act as baffles to the upward migration of the CO_2. On average, the sand packages between the individual mudstone layers are approximately 30 m thick.

On geophysical logs the reservoir characteristically shows a sharp top and base (Figure 4), with the proportion of clean

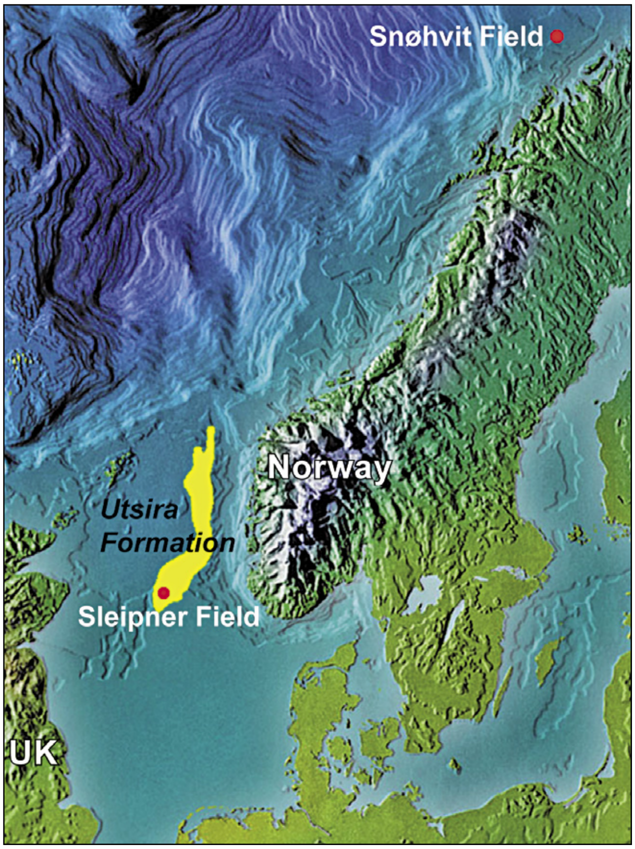

***Figure 1** Map of the Utsira Sand.*

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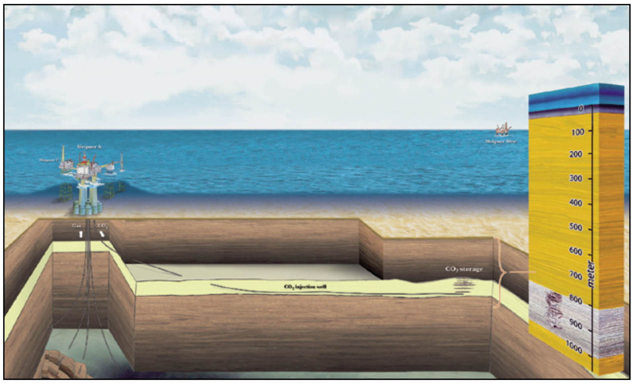

Figure 2 *Scheme of the CO_2 injection at Sleipner.*

sand in the reservoir unit generally varying between 0.7 and 1.0. The shale fraction mostly corresponds to the thin mudstones, which show as peaks on the gamma-ray, sonic and neutron density logs, and also on some induction and resistivity logs. In the Sleipner area, a thicker mudstone, 6-7 m thick around the injection point, separates the uppermost leaf of the sand from the main reservoir beneath.

Correlation of individual thin mudstones from well to well is possible over distances up to about 1 km in the case of closely spaced wells. However, over distances of several kilometres, such as between exploration wells, unambiguous correlation is not possible. Moreover, as the mudstones are not clearly resolved on the baseline (pre-injection) seismic data, their geometry, distribution, and continuity form a large uncertainty in reservoir modelling.

The Utsira Sand is overlain by the Nordland Formation (Isaksen and Tonstad, 1989), which mostly comprises prograding deltaic wedges of Pliocene age. These generally coarsen upwards, from shales in the deeper, axial parts of the basin to silt and sand in the shallower and more marginal parts. In the Sleipner area the lower shale package is between 200 and 300 m thick and forms the main reservoir cap rock. Core material (Figure 3b) is typically a grey to dark grey silty mudstone, uncemented and plastic, and generally homogeneous with only weak indications of bedding.

Gas transport testing on core material (Harrington et al., 2008) indicates that the Sleipner cap rock has acceptable sealing capacity, capable of holding a super-critical CO_2 column of least 100 m and perhaps up to 400 m, depending on the density of the CO_2 (which is very sensitive to pressure and temperature at the reservoir top). This is significantly in excess of buoyancy pressures likely to be encountered in the Utsira Sand, where maximum confined column heights are generally <10 m.

Reservoir simulation

A reservoir flow simulation has been constructed from the geological model. Uncertainty in the geometry and lateral extent of the thin mudstones required simplifying assumptions to be made. Based upon the nearest well logs and on the

Figure 3 *Photos of core material from Sleipner: (a) Utsira Sand and (b) cap rock.*

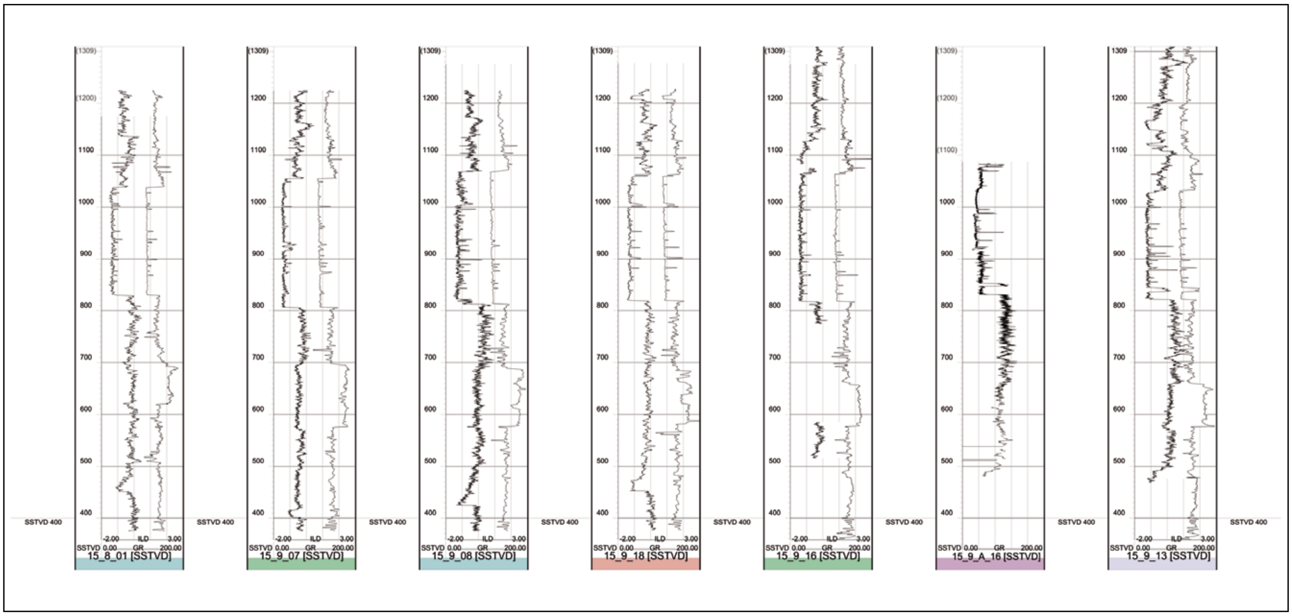

Figure 4 *Well log correlation panel (left trace = gamma ray log and right trace = resistivity log) of the Utsira Sand in yellow and the cap rock in green from west to east. Total length is approximately 20 km. The most eastern wells 15/9-A16 (injection well) and 15/9-13 are closest to the CO$_2$ plume (< 3 km).*

first repeat time-lapse seismic results, eight individual thin mudstones have been defined. These were assigned different structural geometries, ranging from parallel to the reservoir top to a gradational change from parallel to the reservoir top to parallel to the reservoir base.

The effective permeability of the mudstones was adjusted so that the flow simulation approximately matches the estimated amounts of CO$_2$ observed on the successive seismic monitoring surveys (Figure 5). Taking uncertainties into account, the global match between the seismic observations and the reservoir simulation results is reasonable. The main discrepancy concerns detailed lateral spreading patterns of the CO$_2$ beneath the thin mudstones.

Injected CO$_2$ will have temperatures and pressures close to the critical point. At the injection point (1012 m below m.s.l.), virgin temperatures based on measurements in nearby wells and on regional knowledge of the temperature gradient are estimated to be 41±1ºC. Downhole pressure is hydrostatic and varies from ~8 MPa at the top of the reservoir to ~11 MPa at the bottom (Baklid et al., 1996). Around 1.5–2% methane and heavier hydrocarbons are injected together with the CO$_2$, causing significant uncertainties in density and solubility of injected CO$_2$. Numerical flow modelling suggests that part of the CO$_2$ may be in the gaseous phase, but most is in the supercritical state.

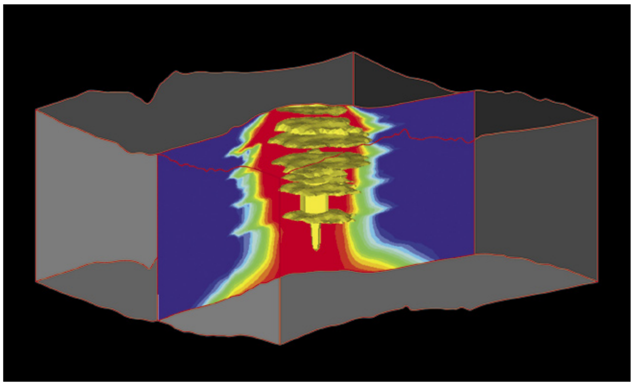

Figure 5 *Snapshot at 2002 of a reservoir simulation in the Utsira Sand with shale baffles. Yellow indicates the isosurface of 95% free CO$_2$. The red color indicates the dissolved CO$_2$.*

Seismic monitoring of the CO$_2$ plume

An extensive seismic monitoring programme has been carried out over the CO$_2$ injection area. Baseline 3D seismic data were acquired in 1994 with repeat surveys in 1999, 2001, 2002, 2004, and 2006 with, respectively, 2.30, 4.20, 4.97, 6.84, and 8.4 million tonnes (Mt) of CO$_2$ in the reservoir.

Predicted changes in seismic response were based on acoustic rock properties estimated from well logs and assumed acoustic properties of CO$_2$ under reservoir pressure and temperature conditions (using a published equation of state, calibrated by laboratory data). A range of densities and bulk moduli were used to address uncertainty on CO$_2$ properties. Because CO$_2$ has a high compressibility, and the Utsira Sand has a weak rock frame, compressional velocity V_p is unusually sensitive to the pore fluid. Substitution of water by CO$_2$ induces a reduction in V_p of up to 30%, even for moderate saturations (Eiken et al., 2000; Arts et al., 2004a).

The effect of CO$_2$ on the seismic data at Sleipner is evident. 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 6).

Reflections are interpreted as arising from up to nine discrete layers of high saturation CO$_2$, each up to a few metres thick, trapped beneath the intra-reservoir mudstones (Chadwick et al., 2004, 2005). The two main effects determining the seismic response are:

- 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 modelling has shown that as the thickness of the CO$_2$ column increases from 0 to 8 m, a gradual increase of the (nega-

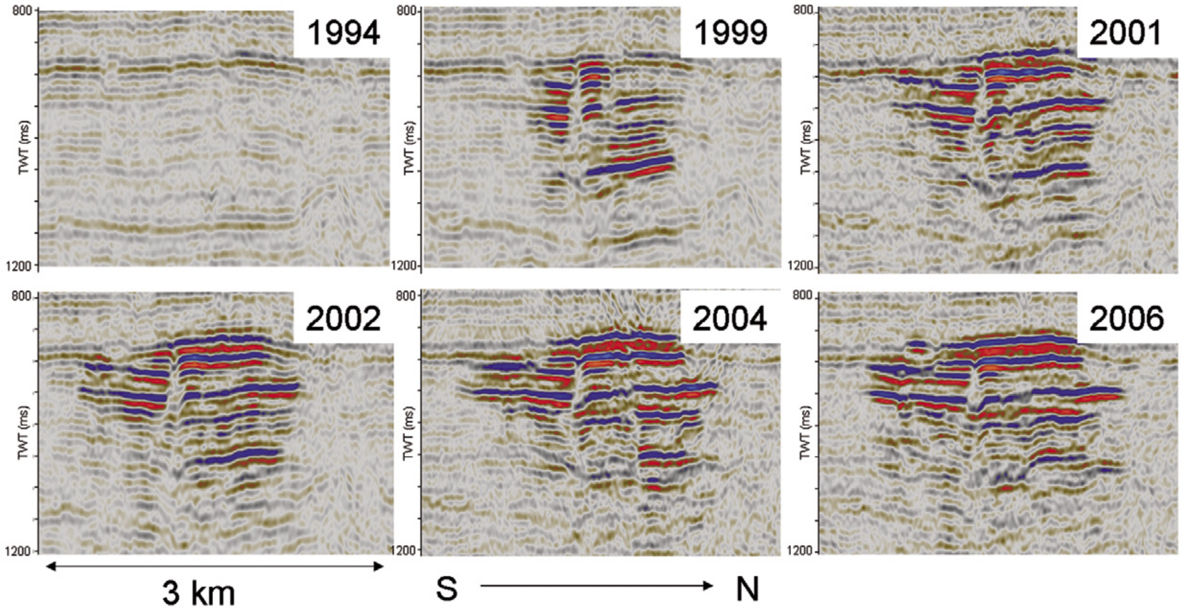

Figure 6 *Development of the CO$_2$ plume over the years imaged with seismic data.*

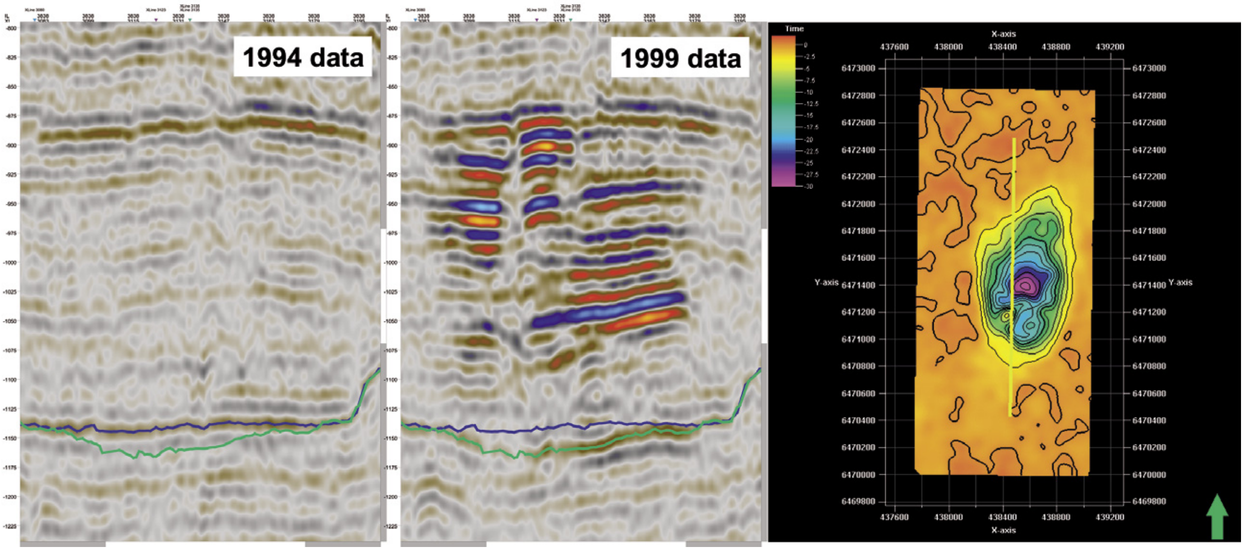

Figure 7 *Velocity pushdown map (right) with time shifts mapped through cross-correlation and manual interpretation between the 1994 and 1999 time-lapse seismic data. The horizons indicate the base Utsira Sand interpreted on the 1994 seismic data (blue) and on the 1999 data (green).*

tive) amplitude is observed (Arts et al., 2004b). Maximum reflection amplitude corresponds to a CO_2 thickness of about 8 m, the so-called 'tuning thickness'.

The velocity pushdown (time-shift) of the seismic data has been determined by cross-correlating the seismic signals below the CO_2 bubble of the 1994 seismic survey (before injection) with the different time-lapse seismic surveys. From the cross-correlations, in places augmented by manual interpretation, a time shift due to velocity changes has been estimated and mapped. The largest effect occurred from 1994 (pre-injection) to 1999 (the first time-lapse survey), with time shifts of more than 30 ms (Figure 7). This would correspond to a local 100% CO_2 saturated rock column of more than 90 m. Quantification studies, using plume reflectivity and velocity pushdown, are described in Chadwick et al. (2005, 2006a).

The development of the CO_2 plume at the different trapping levels can be followed nicely through time. CO_2 reached the top of the reservoir in 1999 with, as observed previously (Chadwick et al., 2005, 2006a,b), clear evidence of buoyancy-driven filling of a small topographical trap at the top of the reservoir, confirming the spreading of CO_2 beneath the cap rock. There is no evidence so far of CO_2 migrating into the overburden. In general terms, the middle and upper parts of the plume have become more reflective with time and continue to spread laterally, controlling the overall extent of the plume (Figure 8).

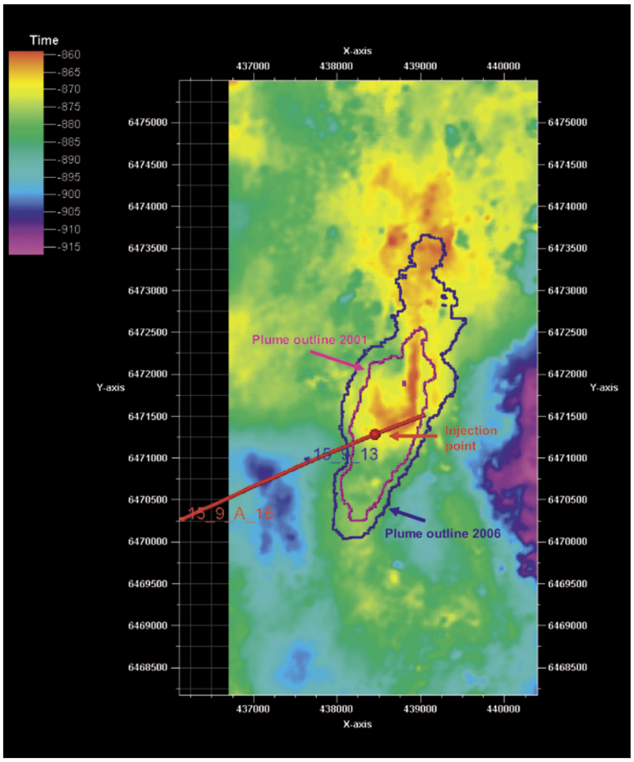

Figure 8 *Outlines of the extent of the CO_2 plume in 2001 and 2006 over the top structure map (in colour) of the top Utsira Sand.*

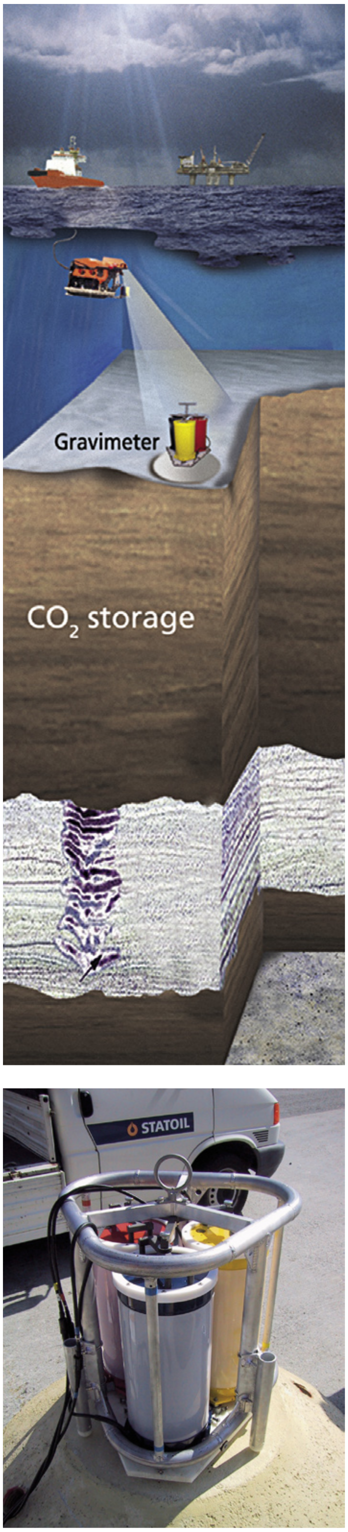

Figure 9 *Cartoon of the seabed gravity acquisition (top) and of a gravimeter (bottom).*

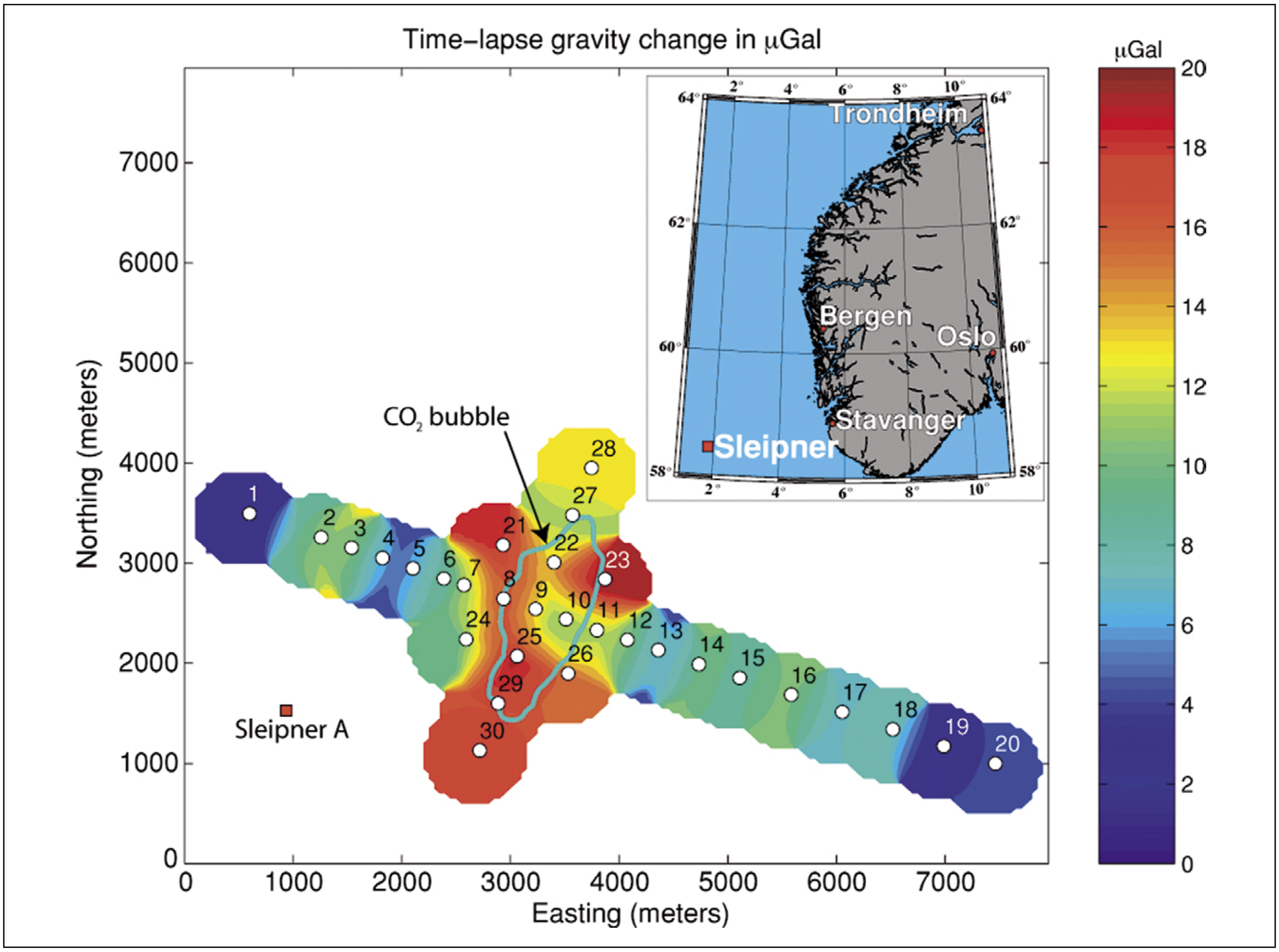

Figure 10 *Time-lapse gravity response from 2002 to 2005. Seabed benchmark locations are shown by white circles with a smoothed version of the gravity changes after correcting for depth and a long wavelength trend. Note the spatially coherent gravity decrease in the central part of the survey (blue line shows extent of the seismically imaged CO$_2$ plume in 2001).*

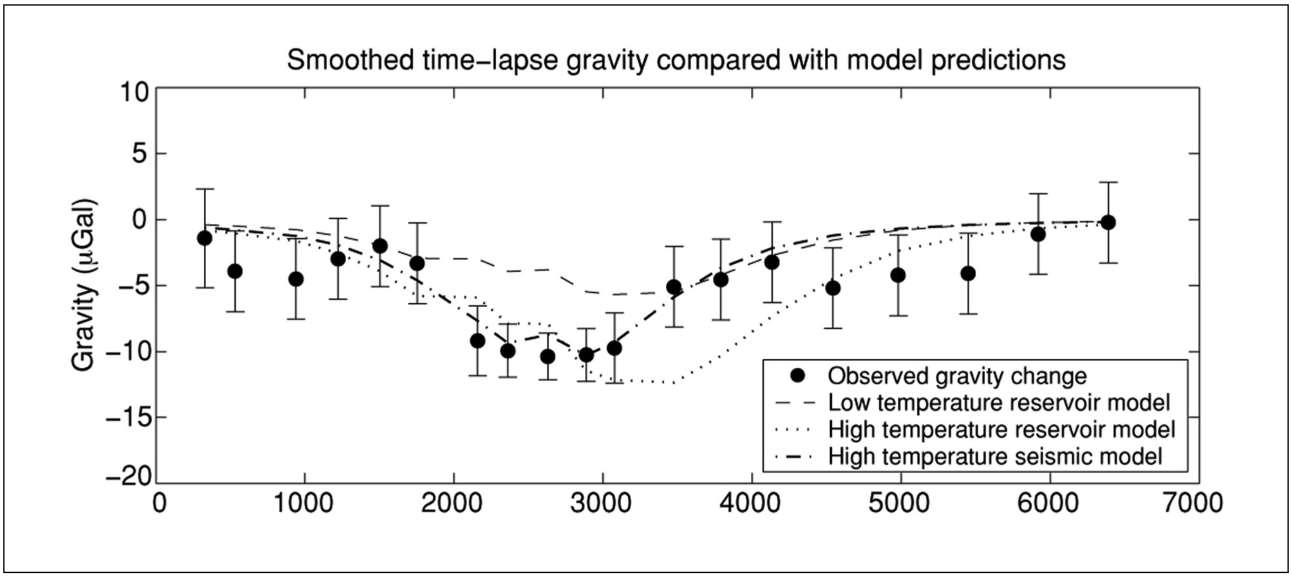

Figure 11 *Smoothed observed time-lapse gravity change plotted with modelled gravity change for high (average CO$_2$ density 550 kg m^{-3}) and low reservoir temperatures (average CO$_2$ density 700 kg m^{-3}) models. Both the models and the observations have been smoothed by averaging neighbouring values. Observed gravity changes most closely match the high temperature seismic model.*

Constraining uncertainties with seafloor gravity monitoring

Time-lapse seafloor gravity monitoring has been carried out at Sleipner. The possibility of detecting injected CO_2 with repeated gravity measurements is strongly dependent on its density and subsurface distribution. Since an initial feasibility study indicated measurable changes (Williamson et al., 2001), a first seabed gravity survey was acquired at Sleipner in 2002, with 5.19 Mt of CO_2 in the plume. The survey was based around pre-positioned concrete benchmarks on the seafloor that served as reference locations for the (repeated) gravity measurements. Relative gravity and water pressure measurements were taken at each benchmark using a customized gravimetry and pressure measurement module mounted on a remotely operated vehicle (Figure 9).

Thirty benchmarked survey stations were deployed in two perpendicular lines, spanning an area some 7 km east-west and 3 km north-south and overlapping the subsurface footprint of the CO_2 plume (Figure 10). Each survey station was visited at least three times to better constrain instrument drift and other errors. Single station repeatability was estimated to be 4 µGal. For time-lapse measurements an additional uncertainty of 1–2 µGal is associated with the reference null level. The final detection threshold for Sleipner, therefore, is estimated at about 5 µGal for individual stations, and somewhat less for a model fit across the grid.

Based upon computation of the gravity response of gridded 3D plume models, with detailed CO_2 distributions and densities defined by reservoir flow simulations (the latter calibrated by the seismic monitor surveys), four model scenarios were considered: a lower temperature reservoir with and without CO_2 dissolution, and a higher temperature reservoir with and without dissolution. The gravity response was computed for 2002 and for 2005 together with the changes from 2002 to 2005 (Table 1).

Depending on temperature and dissolution, the 2002 plume showed a modelled response ranging from -11 to -31 µGal, and the 2005 plume from -16 to -44 µGal. The largest signal corresponds to the higher temperature (low CO_2 density) model with no CO_2 dissolution and shows a predicted maximum change from 2002 to 2005 of around -13 µGal. In contrast, the lower temperature (high CO_2 density) model with CO_2 dissolution has a predicted change from 2002 to 2005 of only about -5 µGal.

In September 2005 the repeat gravity survey was carried out with around 7.76 Mt of CO_2 in the plume, an additional 2.57 Mt compared with the 2002 survey. Each station was visited at least twice. Gravity measurements were corrected for tides, instrument temperature, tilt, and drift. The uncertainty for this survey is estimated at 3.5 µGal. The time-lapse gravimetric response due to CO_2 was obtained by removing the modelled gravimetric changes from Sleipner East (the deeper gas reservoir currently in production) from the measured gravity changes between 2002 and 2005 (Figure 10).

Finally, forward modelling was performed (Nooner et al., 2007) to estimate average in situ CO_2 density. The best fit was obtained for the higher temperature seismically-constrained model (Figure 11). Average CO_2 density is estimated at 530±65 kg m^{-3} (95% confidence interval), consistent with reservoir temperatures as described above.

Further repeat surveys in a few years' time will have a much higher gravity change to measure, with correspondingly greater confidence in the density estimates.

Conclusions

CO_2 storage at Sleipner has been very successful over the last decade with no indications of migration into the reservoir overburden. The combination of seismic monitoring with seabed gravimetry has helped to constrain the reservoir simulation model and to gain insight into the flow behaviour of the CO_2 in the reservoir.

	August 2002 (4.8 Mt)			August 2005 (7.4 Mt)			
	CO_2 density	CO_2 dissolved	Signal	CO_2 density	CO_2 dissolved	Signal	Signal change
	kg/m^3	%	µGal	kg/m^3	%	µGal	µGal
Hot, no dissolution	528	0%	-31.3	523	0%	-44.3	-13.7
Hot, dissolution	531	29%	-2.1	529	28%	-29.8	-8.8
Cold, no dissolution	708	0%	-15.6	707	0%	-22.2	-6.7
Cold, dissolution	708	25%	-10.9	707	23%	-16.2	-5.4

***Table 1** Results of the gravity response derived at the extreme values of the temperature within the uncertainty range, both with and without dissolution of CO_2 taken into account.*

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