GEOPHYSICAL MONITORING OF THE CO_2 PLUME AT SLEIPNER, NORTH SEA: AN OUTLINE REVIEW

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Abstract: CO_2 produced at the Sleipner gas field is being injected into the Utsira Sand, a major saline aquifer some 1000m beneath the North Sea. The injection plume is being monitored by geophysical methods. 3D seismic data were acquired in 1994, prior to injection, and again in 1999, 2001 and 2002; seabed gravimetric data were acquired in 2002. The CO_2 plume is imaged on the seismic data as a number of bright sub-horizontal reflections, growing with time, underlain by a prominent velocity pushdown. Quantitative modelling is based on plume reflectivity largely comprising tuned responses from thin layers of CO_2 trapped beneath thin intra-reservoir mudstones, layer thicknesses being mapped according to an amplitude-thickness tuning relationship. Between the layers, a lesser component of much lower saturation dispersed CO_2 is required to match the observed velocity pushdown. However, reservoir temperatures are subject to significant uncertainty, and inverse models of CO_2 distribution, based on lower and higher temperature scenarios, can both produce the observed plume reflectivity and the velocity pushdown. Higher temperature models however require that the dispersed component of CO_2 has a somewhat patchy, rather than uniform saturation. Analysis of the datasets suggests that accumulations of CO_2 as small as 500 tonnes may be detectable under favourable conditions, providing a basis for setting leakage criteria. To date, there is in fact no evidence of migration from the primary storage reservoir.

1. INTRODUCTION

The carbon dioxide injection at the Sleipner field in the North Sea (Baklid *et al.* 1996), operated by Statoil and the Sleipner partners, is the world's first industrial scale CO_2 injection project designed specifically as a greenhouse gas mitigation measure. CO_2 separated from natural gas is being injected into the Utsira Sand (Fig. 1), a major saline aquifer of late Cenozoic age (Chadwick *et al.* 2004a, Zweigel *et al.* 2004). The injection point is at a depth of about 1012 m bsl, some 200 m below the reservoir top. Injection started in 1996, with at the time of writing, more than 7 million tonnes of CO_2 *in situ*.

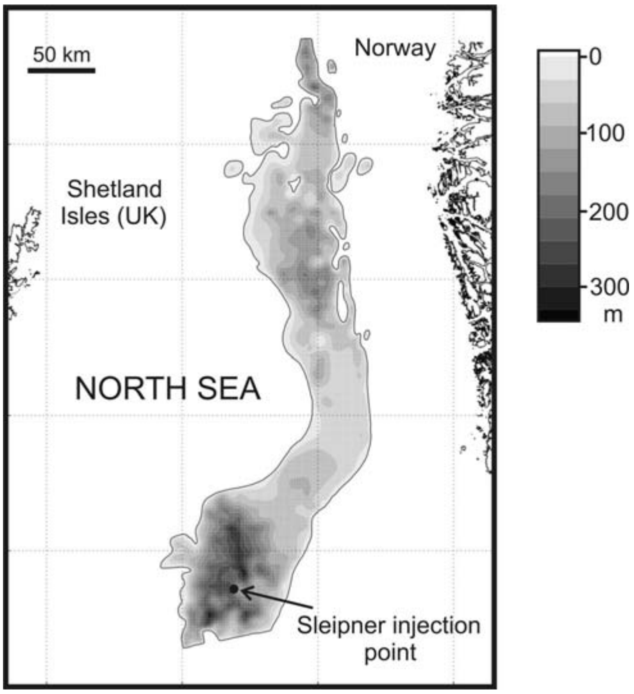

Figure 1. Location map of Sleipner and the Utsira Sand showing aquifer thickness.

Since 1998 the injection operation has been linked to a number of research projects, notably SACS, SACS2 and CO2STORE. These projects, funded by the EU, industry and national governments, aim to show that underground storage is a safe and verifiable technology. Specifically they have carried out scientific research into the geological aspects of the Sleipner injection operation by monitoring and modelling the injected CO_2 plume.

Key aims of the monitoring programme at Sleipner are outlined below:

a) To show that the CO_2 is being confined safely within the primary storage reservoir.
b) To image the distribution and migration of CO_2 through the reservoir and, should it occur, into adjacent strata.
c) To provide early warning of any potentially hazardous migration towards the seabed.

Baseline 3D seismic data were acquired in 1994, prior to injection, with repeat surveys in 1999 (2.35 million tonnes of CO_2 in the reservoir), 2001 (4.26 Mt) and 2002 (4.97Mt). In addition, to complement the information available from the seismic datasets, a seabed gravimetric survey was acquired in 2002.

2. TIME-LAPSE SEISMIC DATASETS

This paper provides a brief outline of current interpretive work on the seismic datasets. Fuller details are given in Arts *et al*. (2004a, 2004b) and Chadwick *et al*. (2004b, 2005).

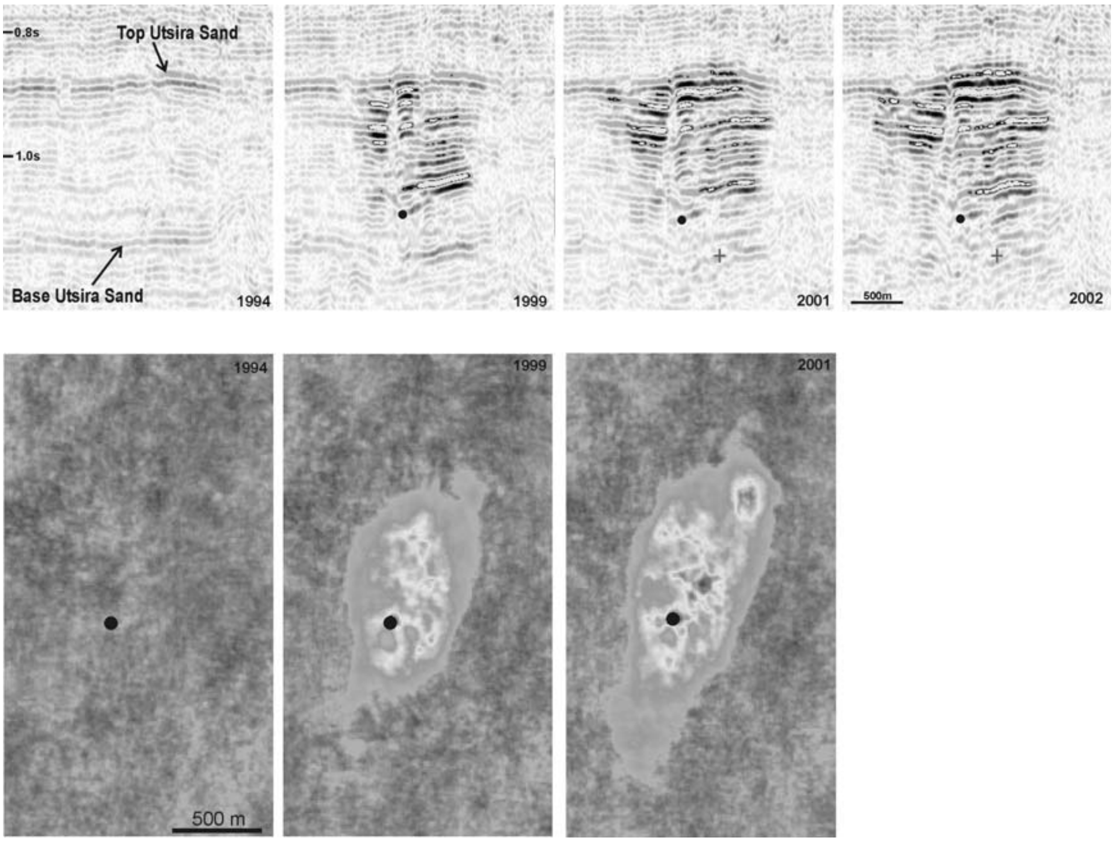

Figure 2. Time-lapse seismic images of the CO_2 plume a) N-S inline through the 1994 dataset prior to injection and through the 1999, 2001 and 2002 datasets. b) Maps of integrated absolute reflection amplitudes from the plume showing its elliptical form in plan view and growth from 1999 to 2001. Black disc denotes injection point.

2.1 Time-lapse images

The CO_2 plume is imaged as a number of bright sub-horizontal reflections within the reservoir, growing with time (Figure 2a). The reflections are interpreted as arising from thin (< 8 m thick) layers of CO_2 trapped beneath thin intra-reservoir mudstones and the reservoir caprock. The plume is roughly 200 m high and elliptical in plan, with a major axis increasing from about 1500 m in 1999 to about 2000 m in 2001 (Figure 2b). The plume is underlain by a prominent velocity pushdown (Figure 3) caused by the seismic waves travelling much more slowly through CO_2-saturated rock than through the virgin aquifer.

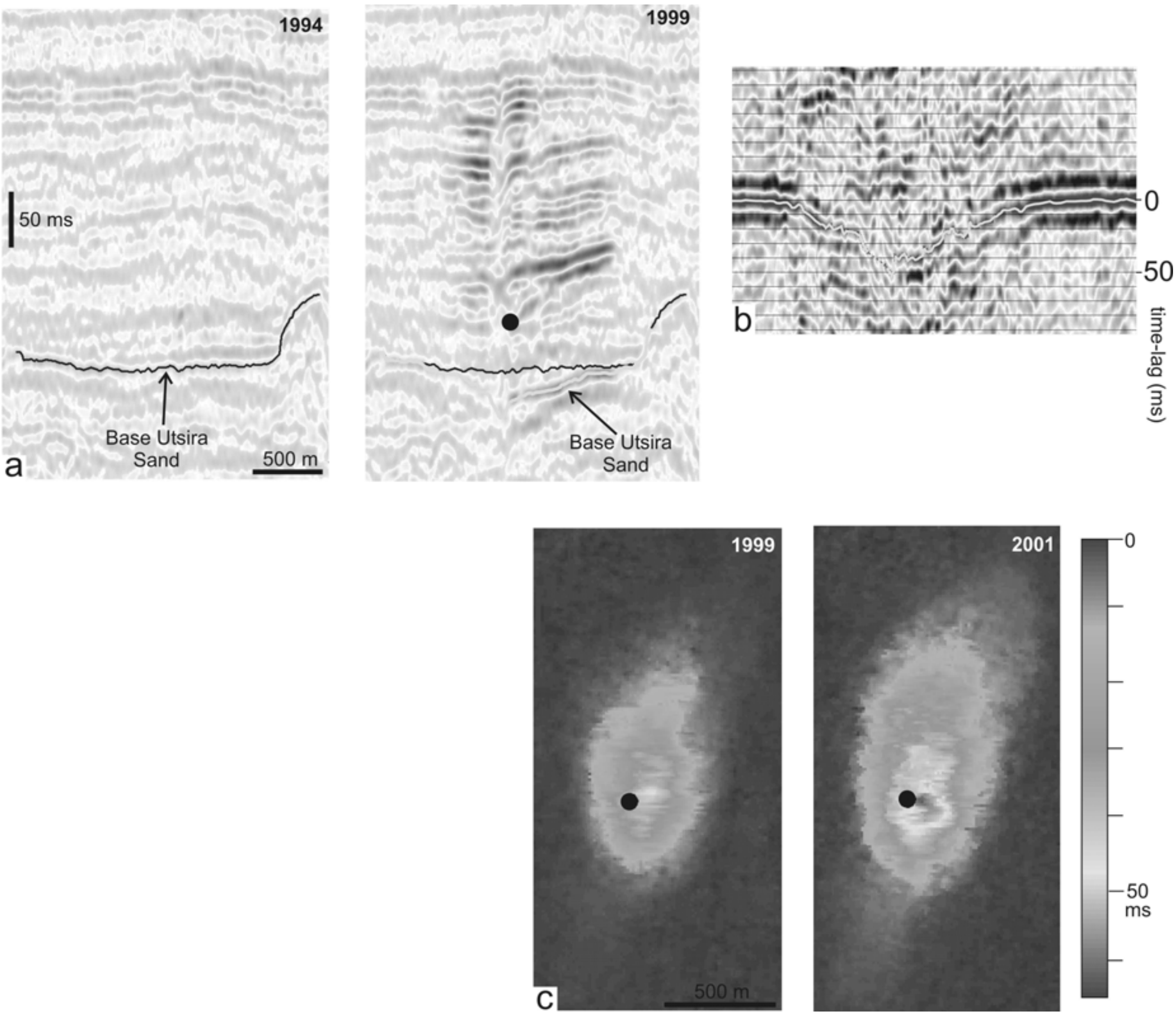

Figure 3. Velocity pushdown. a) Inline through the reservoir in 1994 and 1999 showing pushdown of the Base Utsira Sand beneath the plume. b) Cross-correlogram of a reflection window beneath the central part of the 2001 plume. Pick follows the correlation peak and defines the pushdown. c) Pushdown maps in 1999 and 2001. Black disc denotes injection point.

2.2 Seismic modelling

Seismic modelling aimed at verifying the *in situ* injected mass of CO_2 has utilised both inverse and forward modelling techniques. Forward modelling, via history-matched reservoir-simulations of the CO_2 plume, produces a reasonable match to the observed data (Figure 4), though the detailed geometry of the plume layering remains uncertain.

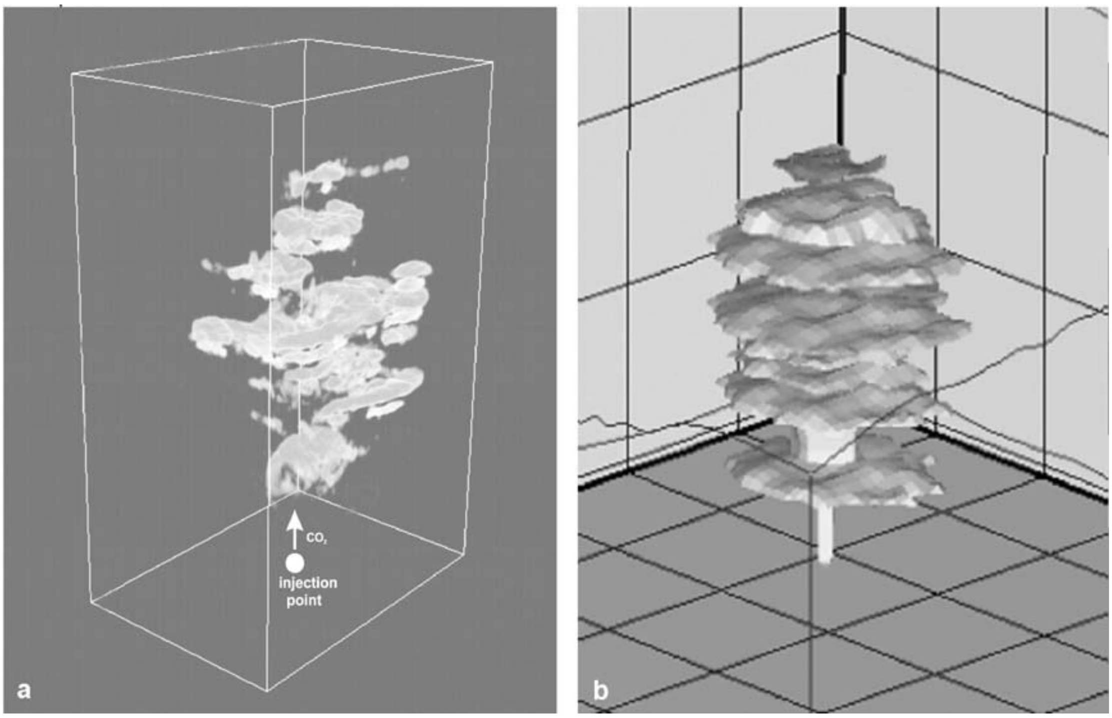

Figure 4. The 2001 plume a) observed seismic data (opacity display of the 2001 minus 1994 difference cube) b) reservoir simulation

Inverse modelling aims to quantify amounts of CO_2 from layer reflectivity and velocity pushdown. Because fluid pressures are believed to have changed very little during injection, modelling is based solely on fluid saturation changes. The observed plume reflectivity most likely comprises tuned responses from thin layers of CO_2 whose thickness varies directly with reflection amplitude. Inverse modelling takes as a starting point, thin, high saturation layers of CO_2, mapped according to an amplitude-thickness tuning relationship. This is supported by structural analysis of the topmost CO_2 layer, whose thickness, estimated directly from the top reservoir topography, varies directly with reflection amplitude. In addition, in order for the modelled CO_2 distributions to produce the observed velocity pushdown, a minor, intra-layer component of much lower saturation CO_2 is required.

A measured formation temperature of 36°C is available for the Utsira reservoir, but is poorly-constrained. Regional temperature patterns suggest that the reservoir may be up to 10°C warmer. At the higher temperatures, CO_2 would have significantly different physical properties. In particular its density would be significantly lower, giving a correspondingly larger *in situ* volume. Inverse models of CO_2 distribution in the 1999 plume have been generated, based on both the measured, and a possible higher temperature scenario (Figure 5). The distribution of CO_2 in both models is consistent with the known injected mass (allowing for parameter uncertainty) and can replicate the observed plume reflectivity and the velocity pushdown. However, the higher temperature model requires that the dispersed component of CO_2 has a somewhat patchy, rather than uniform mixing of the CO_2 and water phases (Sengupta & Mavko 2003). This highlights a key uncertainty in verification estimates; the velocity behaviour of the CO_2 – water – rock system, which is heavily dependent on the (poorly constrained) nature of small-scale mixing processes between the fluid phases.

Because of these uncertainties, a modelling solution that uniquely verifies the injected volume has not yet been obtained. Work on reducing uncertainty is ongoing.

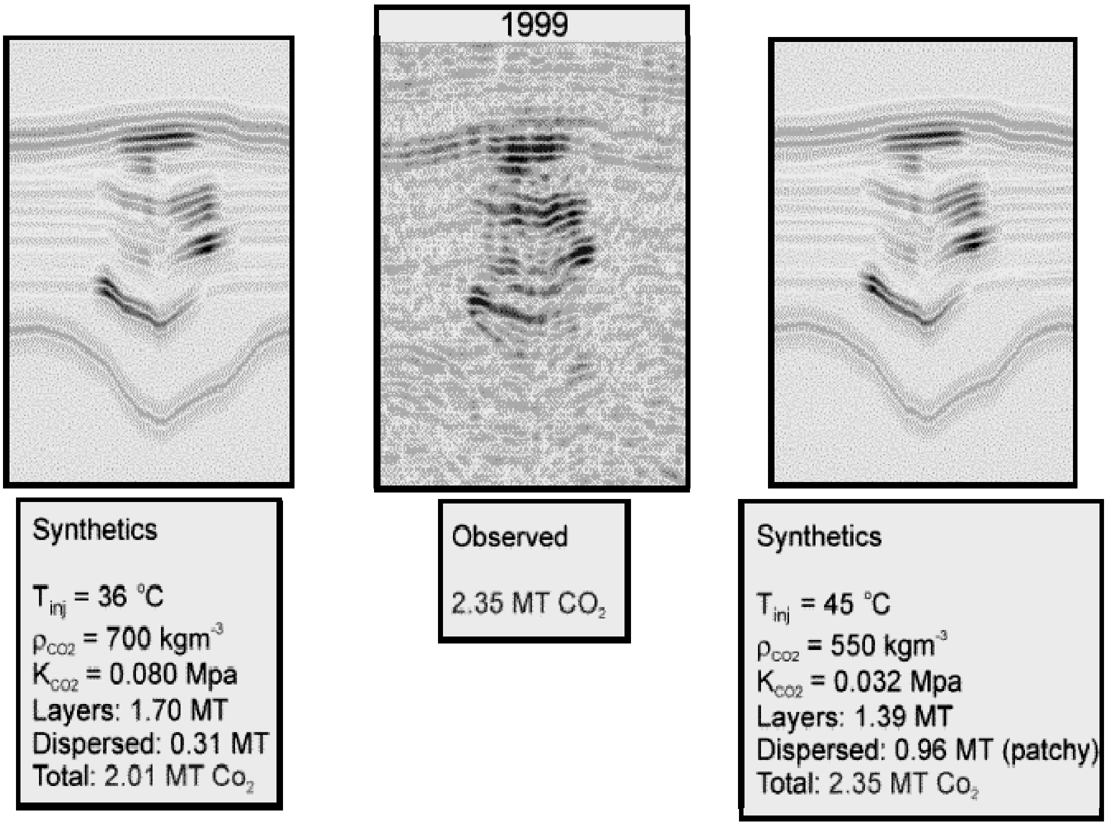

Figure 5. Inverse modelling of the 1999 plume. Observed data compared with synthetic seismograms based on inverse models for two plume scenarios: Injection point at 36°C with fine-scale mixing throughout; Injection Point at 45° C with patchy mixing in the intra-layer dispersed component of CO_2.

2.3. Detecting migration from the storage reservoir

The seismic data indicate that no detectable leakage of CO_2 into the caprock has so far occurred. The potential detection capability of the Sleipner data can be illustrated by examining the 1999 plume (Figure 6). The topmost part of the plume is marked by two small CO_2 accumulations trapped directly beneath the caprock seal. From the reflection amplitudes, the volumes of the two accumulations can be estimated at 9000 and 11500 m^3 respectively. Other seismic features on the timeslice can be attributed to repeatability noise, arising from slight intrinsic mismatches between the 1999 and 1994 (baseline) surveys. It is clear that the level of repeatability noise plays a key role in determining the detectability threshold. Thus for a patch of CO_2 to be identified on the data it must be possible to discriminate between it and the largest noise peaks. Preliminary analysis suggests that accumulations larger than about 4000 m^3 should fulfil this criterion. This corresponds to about 2000 tonnes of CO_2 at the top of the reservoir where CO_2 has a density of about 500 kgm^{-3}, but less than 600 tonnes at 500 m depth, where the density is considerably lower. Seismic detection depends crucially on the nature of the CO_2 accumulation. Small thick accumulations in porous strata would tend be readily detectable. Conversely, distributed leakage fluxes through low permeability strata may be difficult to detect with conventional seismic techniques. Similarly, leakage along a fault within low permeability rocks would be difficult to detect. Fluxes of CO_2 such as these may well be associated with changes in fluid pressure, in which case shear-wave seismic data is likely to prove useful as a detection tool.

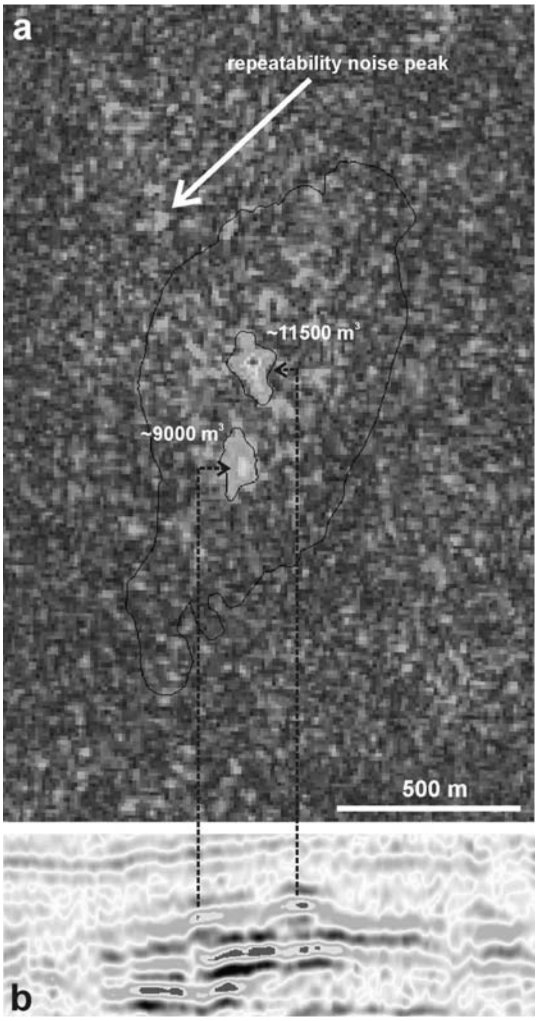

Figure 6. Detection limits for small amounts of CO_2 a) Map of the 1999-94 difference data showing integrated reflection amplitude in a 20 ms window centred on the top Utsira Sand. Note high amplitudes (paler greys) corresponding to the two small CO_2 accumulations. Note also scattered amplitudes due to repeatability noise. b) Part of seismic line showing the topmost part of the plume and the two topmost CO_2 accumulations.

3. TIME-LAPSE SEABED GRAVIMETRY

Measurements of the gravitational acceleration due to mass distributions within the earth may be used to detect variations in subsurface rock or fluid density. Although of much lower spatial resolution than the seismic method, gravimetry offers some important complementary adjuncts to time-lapse seismic monitoring. Firstly, it can provide independent verification of the change in subsurface mass during injection via

Gauss's Theorem. This potentially important capability may enable estimates to be made of the amount of CO_2 going into dissolution, a significant source of uncertainty in efforts to quantify free CO_2 in the reservoir (dissolved CO_2 is effectively invisible on seismic data). Secondly, deployed periodically, gravimetry could be used as an 'early warning system' to detect the accumulation of CO_2 in shallow overburden traps where it is likely to be in the low density gaseous phase with a correspondingly strong gravity signature.

The possibility of monitoring injected CO_2 with repeated gravity measurements is strongly dependent on CO_2 density and subsurface distribution. A feasibility study of time-lapse gravimetry at Sleipner (Williamson *et al.* 2001) modelled plume scenarios with CO_2 densities ranging from over 700 kgm^{-3} (corresponding to the lower reservoir temperature scenario) to less than 350 kgm^{-3} (corresponding to possible higher reservoir temperatures). The modelling indicated that future changes in the CO_2 plume could theoretically be detectable by seabed gravimetry. For example it was shown that addition of 2 million tonnes to the plume would produce a change in peak gravity signal of between -8 and -33 μGal, corresponding to CO_2 densities of 700 kgm^{-3} and 350 kgm^{-3} respectively (Figure 7). Longer-term predictions suggest that the gravity signature of the plume will gradually decrease as it thins by lateral migration at the reservoir top. On the other hand, if CO_2 leaked to shallower levels where it would have a still lower density, gravity changes could well exceed -100μGal.

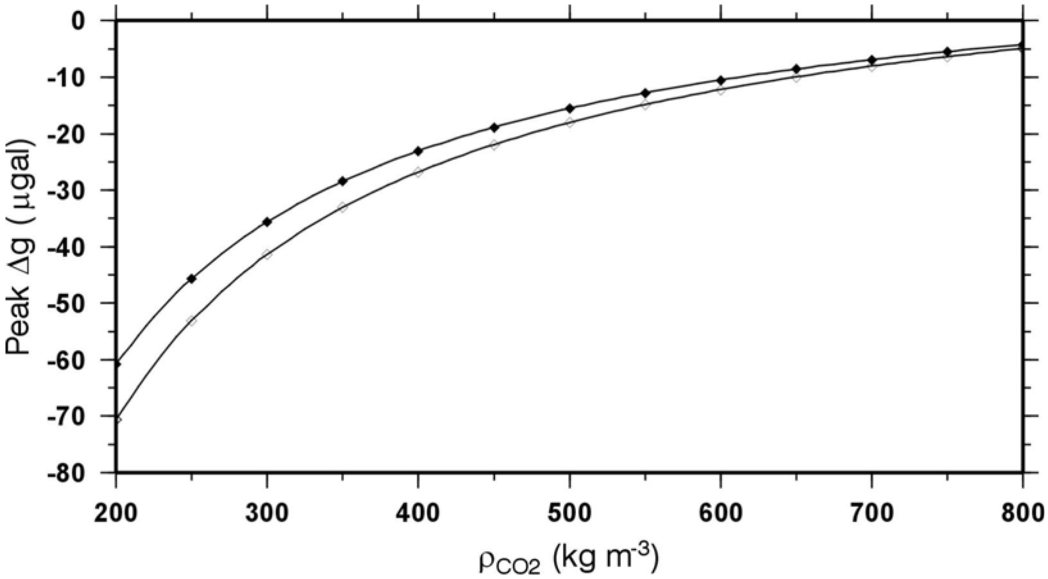

Figure 7. Peak gravity anomaly as a function of CO_2 density, predicted for the Sleipner CO_2 plume in 1999 (2.3 MT in situ). Gravity changes computed for the sea surface (solid symbols) and the seabed (open symbols).

A seabed gravity survey was acquired at Sleipner in 2002 (Eiken *et al*. 2003), with approximately 5 million tonnes 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 by a customised gravimetry and pressure measurement module mounted on a Remotely Operated Vehicle (Figure 8).

Thirty concrete benchmark 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. 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.

A repeat gravity survey is planned for the summer of 2005, with a projected 8 million tonnes of CO_2 in the plume. The additional 3 million tonnes of CO_2 are expected to produce a gravity change of between about -10 and -43 µGal depending on density. Such a change should theoretically be detectable. In the event that acceptably accurate measurements are obtained, it will be possible to derive the average density of CO_2 in the plume. This will help to constrain plume temperatures, which will in turn reduce uncertainty in the seismic analysis.

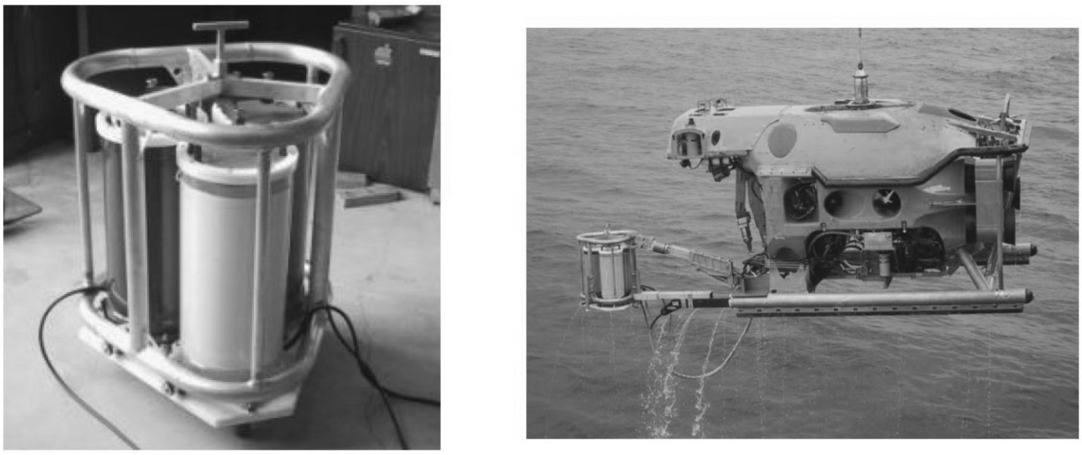

Figure 8. The seabed gravimetry operation at Sleipner showing the seabed gravimetry/pressure instrumentation and the remotely operated vehicle being lowered into the sea.

4. CONCLUSIONS

Time-lapse seismic monitoring has proved notably successful in imaging the growing CO_2 plume at Sleipner. Quantitative analysis of the1999 dataset has shown that the observed seismic signature is consistent with known injected amounts, but a complete verification has not been possible due to a number of uncertainties. These are related both to reservoir properties and conditions and also to the seismic properties of the CO_2 - water - rock system. Gravimetry has so far been restricted to an initial survey, but it is hoped that future repeat datasets will provide additional complementary information that can be used to further reduce seismic uncertainty.

The Utsira Sand is a relatively shallow, thick, reservoir with notably high porosity and permeability. In this respect it is very suitable for both seismic and gravimetric monitoring, with injected CO_2 giving rise to particularly pronounced geophysical signatures. Other storage scenarios are likely to prove more challenging from a monitoring standpoint. In addition to Sleipner, industrial-scale CO_2 injection projects are ongoing at Weyburn in Canada (Wilson and Monea 2004), and at In Salah in Algeria, with another planned for the Snohvit field in the Barents Sea. These will further test the efficacy of geophysical monitoring methods in a range of storage situations. Reservoir depths range from ~ 1500m to nearly 3000 m, with widely different reservoir types including carbonates. Major research projects are linked to all of these projects and important new insights into monitoring capabilities are anticipated in the coming years.

5. ACKNOWLEDGEMENTS

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