# A Sea Floor Gravity Survey of the Sleipner Field to Monitor $CO_2$ Migration

**Technical Progress Report**

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## Abstract

Since 1996, excess $CO_2$ from the Sleipner natural gas field has been sequestered and injected underground into a porous saline aquifer 1000 m below the seafloor. In 2002, we carried out a high precision micro-gravity survey on the seafloor in order to monitor the injected $CO_2$. A repeatability of 5 μGal in the station averages was observed. This is considerably better than pre-survey expectations. These data will serve as the baseline for time-lapse gravity monitoring of the Sleipner $CO_2$ injection site. A repeat survey has been scheduled for the summer of 2005. This report covers 3/18/04 to 9/19/04. During this time, we participated in several $CO_2$ sequestration-related meetings and conferences. On March 29, 2004, we participated in the 2004 Carbon Sequestration Project Review Meeting for the Department of Energy in Pittsburgh, PA. During the week of May 2, 2004, we attended and presented at the Third Annual Conference on Carbon Capture and Sequestration in Alexandria, VA. Finally, during the week of August 8, 2004, we took part in the U.S.-Norway, $CO_2$ Summer School in Santa Fe, NM. Additional modeling was also completed, examining the seismic velocity pushdown estimates from the gravity models and the expected deformation of the seafloor due to the injected $CO_2$.

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## Executive Summary

This document is a report detailing the continuing work that has been done under DOE Award DE-FC26-02NT41587, which started September 19, 2002. This work, the quantification of gravity change associated with the sequestration of $CO_2$ at the Sleipner gas field in the North Sea, is a collaborative research effort between US scientists and members of the SACS (Saline Aquifer $CO_2$ Storage) consortium. At this site, about 1 Mton of excess $CO_2$ is extracted from the natural gas each year and then injected into a porous saline aquifer (the Utsira formation) at about 1000 m below the seafloor (Baklid et al., 1996). Because $CO_2$ has never been compressed and injected underground for sequestration before, it is important to monitor what happens as time passes.

As this gas is injected into the storage reservoir, the overall density of the rock and pore space decreases. This decrease in density has an effect on the local strength of gravity. By monitoring how the local gravity field changes with time, we can assess the extent to which the gas is successfully contained and we can put constraints on the density of $CO_2$ within the reservoir.

Near predicted reservoir temperature and pressure conditions, $CO_2$ goes through a critical phase transition in which the density changes from 200 kg/m$^3$ to over 700 kg/m$^3$ over a short range of temperature (Span and Wagner, 1996). Thus, a slightly higher temperature could result in a much lower $CO_2$ density. Therefore, a feasibility study for monitoring the $CO_2$ bubble expansion by time-lapse gravity measurements was done by Williamson et al., (2001). They computed the gravity signals from both a high and a low-density model. The low-density model (350 kg/m$^3$) shows a peak anomaly of -34 μGal, while the high-density model (700 kg/m$^3$) shows a peak anomaly of -7 μGal after 2.268 MT of $CO_2$ was injected (slightly over two years). If significant amounts of $CO_2$ penetrate above the top seal, density will be further reduced and the gas will be closer to the observation points, causing gravity changes that could well exceed 100 μGal, making gravity an effective tool for measuring catastrophic leaks.

Gravity was measured on the seafloor above the Sleipner $CO_2$ injection site from the 15$^{th}$ to the 21$^{st}$ of August 2002, on top of 30 concrete benchmarks, which were permanently deployed on the seafloor. The area spans about 7 km E-W and 3 km N-S. In relative gravity surveys, the uncertainty is given by the repeatability of the measurements, thus each benchmark was visited at least three times. Repeatability for a single gravimeter is estimated to be 4.3 μGal. These data will serve as a baseline for future monitoring of the $CO_2$ bubble. For time-lapse measurements, there is additional uncertainty associated with the reference benchmark, determined from stations outside the $CO_2$ area, of about 1-2 μGal. Therefore, the final detection threshold for time-lapse changes is about 5 μGal. This is considerably better than the pre-survey expectations of 10 μGal, and increases the likelihood of detecting time-lapse changes. Single observation relative depth estimates have a repeatability of 0.5 cm, which also makes monitoring of small vertical seafloor movements in the area possible.

Based on the original survey alone, a limited amount of information about the injected $CO_2$ can be obtained. A future repeat gravity survey is the only way to provide an independent and reliable means to quantify the $CO_2$. We expect that in a second survey, any gravity change will be due to the changing $CO_2$ volume, not the presumed stable geologic setting. A repeat survey is scheduled for the summer of 2005.

We developed our own software to do the gravity modeling, since no commercial software could do what we needed. Using this software, we have been able to place bounds on the expected time-lapse gravity signal, which will allow us to constrain the $CO_2$ density within the reservoir. For low density $CO_2$, we expect to see a gravity change of 7-9 μGal/year and for high density $CO_2$ we expect to see a gravity change of 2-3 μGal/year. For a 3-year span between surveys (2002-2005), this means a maximum gravity change between 27 μGal or 9 μGal, depending on the $CO_2$ density within the reservoir. By calculating the seismic velocity pushdown (time delay in the two-way vertical travel time), some constraints can be placed on the geometry of the intra-reservoir $CO_2$. Deformation of the seafloor could also provide information about the stored $CO_2$. Mechanical modeling of the reservoir indicate that the maximum possible uplift expected is ~0.16 cm/yr, or about 0.5 cm over 3 years. However, the depth resolution of our seawater pressure measurements (obtained along with gravity) is about 0.5 cm, based on the repeatability of the pressure measurements in the first survey. Therefore, we don't expect to see a seafloor deformation signal in within the first 3 years.

## Experimental

In microgravity reservoir monitoring surveys on land (e.g. Allis and Hunt, 1986; San Andres and Pedersen, 1993) accuracies of 10 μGal or better have been achieved by careful use of standard gravimeters. However, ship-borne measurements have uncertainties of several hundreds of μGal, making offshore gravity monitoring difficult. A new seafloor gravimeter (ROVDOG for ROV deployed Deep Ocean Gravimeter) has been developed by Scripps Institution of Oceanography and Statoil (Sasagawa et al., 2003; Eiken et al., 2000). The collection of seafloor gravity data is desirable because the signal-to-noise ratio is significantly better than that of sea surface data. The primary benefit, however, is that the ROVDOG is placed directly on the seafloor and is connected to the deployment vehicle via only a loose tether, eliminating all accelerations caused by ship and vehicle. Also, by deploying the instrument with an ROV onto seafloor benchmarks, positioning uncertainties related to site reoccupation are virtually eliminated.

Water pressure is also measured in our instrument package for high-accuracy relative depth measurements. Separate stationary reference pressure gauges are also deployed for the survey period to record tidal signals, which need to be taken out of the relative pressure records.

The primary sensor in the ROVDOG instrument is a modified Scintrex CG-3M gravimeter mounted in a compact gimbal platform for leveling and enclosed, along with a Paroscientific 31K pressure gauge, in a watertight pressure case. Three pressure cases were mounted on a frame (Figure 1). The instrument is described in more detail in Sasagawa et al. (2003).

**Figure 1: ROVDOG II**

Benchmarks were deployed in a 10-hour period just before surveying, on August 16, 2002. 20 of the benchmarks were placed in a 7.3 km long WNW-ESE profile across the injection point (Figure 2). The distance between stations increases from about 300 m near the injection point up to 500 m towards the ends. Another 10 locations span the orthogonal dimension and cover the extent of the $CO_2$ accumulation in 2002.

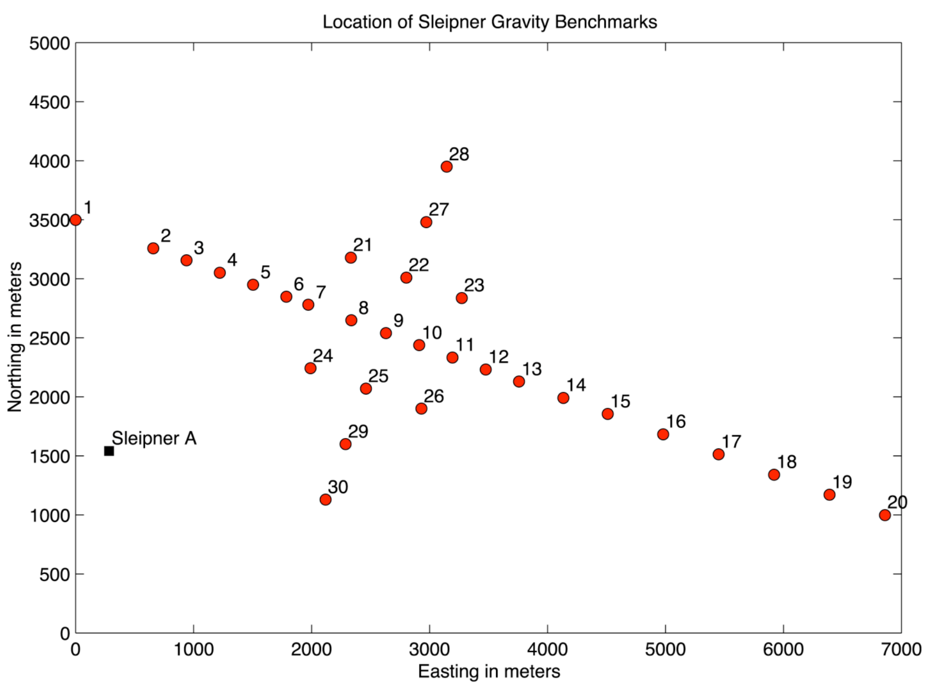


**Figure 2. Sleipner gravity benchmark locations are shown in red.**

The gravity data were analyzed in collaboration with Ola Eiken and Torkjell Stenvold from Statoil (as discussed in previous technical reports). We found the repeatability of the meters to be about 2.5 μGal, making the observable signal size from a time-lapse measurement about 5 μGal.

After investigating and testing the commercial software, we realized that we needed to write our own code to do the 3-D gravity modeling. The primary reasons behind this are 1. We needed to calculate gravity from an arbitrary shape, 2. We needed to be able to compute the gravity from a volumetric grid (from the SINTEF reservoir simulation models), and 3. We needed to vary the density of the arbitrarily shaped body both horizontally and vertically. This led us to develop code to construct mass bodies from either a collection of cuboids or point masses.

This code was then used to calculate the expected gravity change for a range of models. This is discussed in more detail below along with a summary of the meetings and conferences we took part in over the next 6 months.

## Results

### *Gravity Modeling*

We estimated the time-lapse gravity signal from two sets of models. In the first method, we took the seismically imaged $CO_2$ horizons for 1999 and 2001 and built a model based on them (Figure 3). The amplitudes of the horizons were linearly related to layer thickness with the maximum reflection amplitude being set equal to 8 m (Arts et al., 2002). This corresponds to the tuning thickness of the seismic wavelet (about 8 m in this case). The total mass of $CO_2$ was then calculated and compared to the known injected mass. The 'unaccounted for' mass was then put into a low saturation volume encompassing the horizons. This was done to take into account the requirement of the seismic pushdown effect to have a low saturation volume of $CO_2$. The seismic pushdown effect is caused by a decrease in seismic velocity through the $CO_2$ that has taken the place of water in the pore spaces within the reservoir. This decrease in velocity causes a corresponding increase in the travel-time of the seismic wave, causing a downward dip in the apparent horizontal layer depth (this can be seen in Figure 3).

The time-lapse gravity signal was computed by comparing the results from the model based on the 2001 seismic data to the model based on the 1999 seismic data assuming a 1 MT/year injection rate. This was done for a high $CO_2$ density ($\rho_{co_2}$ = 700 kg/m$^3$) scenario and a low $CO_2$ density ($\rho_{co_2}$ = 350 kg/m$^3$) scenario. The results are that for the high-density scenario we expect to see a change of about 2 μGal/year and for the low-density scenario we expect to see a change of about 6 μGal/year (Figure 4).

The second type of model was based on reservoir simulation models done by SINTEF. We calculated the gravity on the seafloor directly from 3-D grids that came directly from their simulations. Two types of simulation models were examined. The first type has a central chimney and horizontal $CO_2$ layers like the seismic model; however, it has no low saturation volume (Figure 5a). The engineers at SINTEF have not been able to produce a $CO_2$ flow scenario resulting in a low saturation volume as suggested by the seismic pushdown. Therefore, a second model was examined, composed of several micro-chimneys, which might look like a diffuse volume of $CO_2$ to the seismics (Figure 5b). The simulation models were computed by SINTEF using an injected mass of 5.17 MT and a density of $\rho_{co_2}$ = 750 kg/m$^3$. We also wanted the change due to the low-density scenario, so in May, 2004, SINTEF ran their simulation models using a density of 300 kg/m$^3$ for up to 16 years of injection. The results of this modeling indicate that for the high-density case we expect to see a change of about 2-3 μGal/year (depending on whether or not the micro-chimneys exist) and for the low-density case we expect to see a change of about 7-9 μGal/year (Figure 6).

The maximum gravity value predicted by the two types of models agree pretty well, indicating that the detailed geometry of the $CO_2$ bubble will not affect the estimated $CO_2$ density. The shape of the gravity curves (Figures 4 and 6) do reflect the geometry of the $CO_2$ bubble to some extent. However, this will probably be beyond the resolution of the technique for a three year time period.

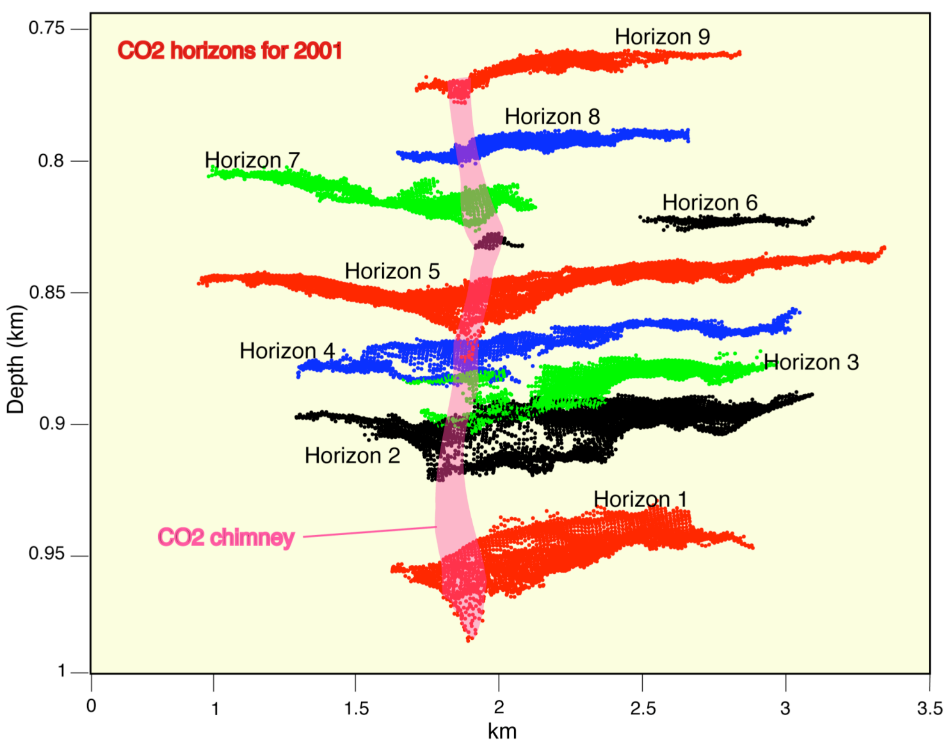


**Figure 3: This shows a side-view of the seismically imaged $CO_2$ horizons. The seismic pushdown in the layers can be seen. The chimney that is drawn in is for illustration only.**

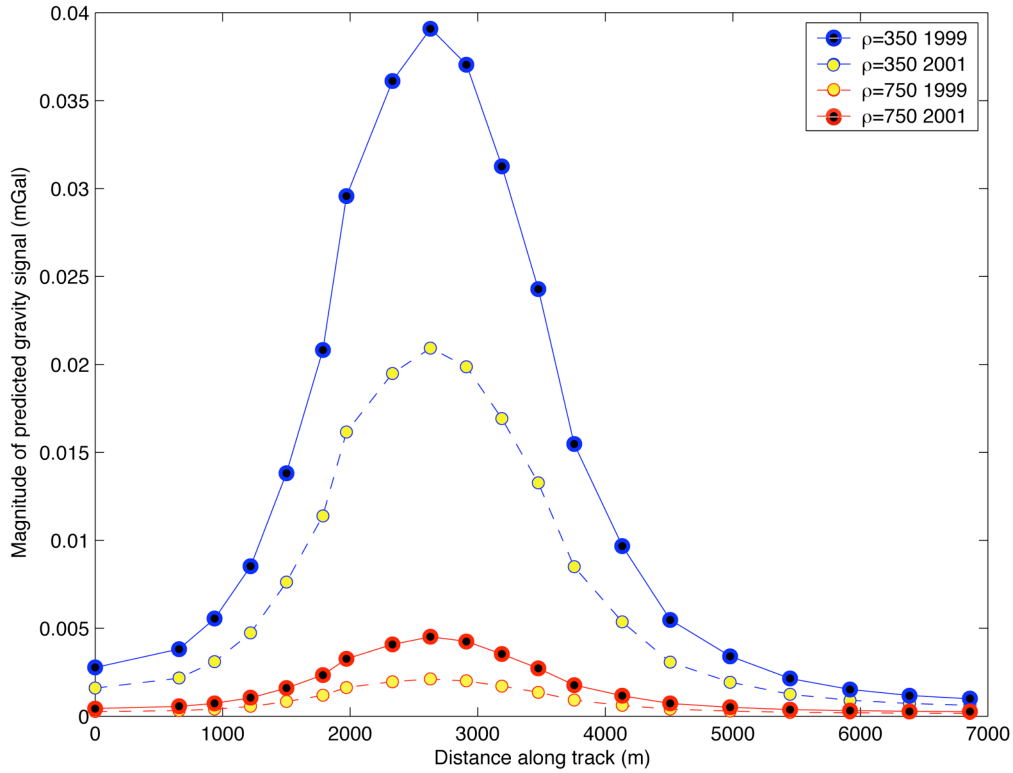


**Figure 4: This shows the gravity change on the benchmarks for a profile across the $CO_2$ bubble as calculated from the seismically imaged horizons. The blue lines show the low-density scenario and the red lines show the high-density scenario.**

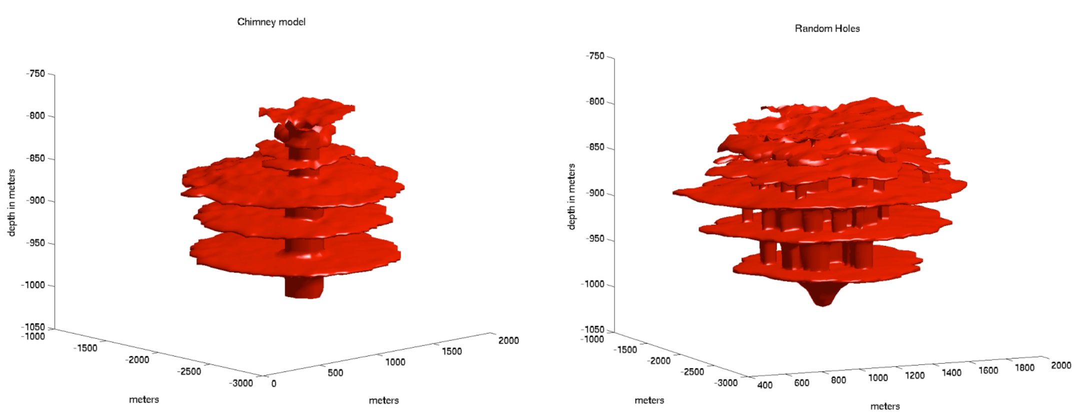


**Figure 5: A). The figure on the left shows the single chimney model from the reservoir simulations. There is not diffuse volume of $CO_2$. B). The figure on the right shows the reservoir simulation model which uses several micro-chimneys to create a situation that might affect the seismic pushdown without needing a diffuse volume of $CO_2$.**

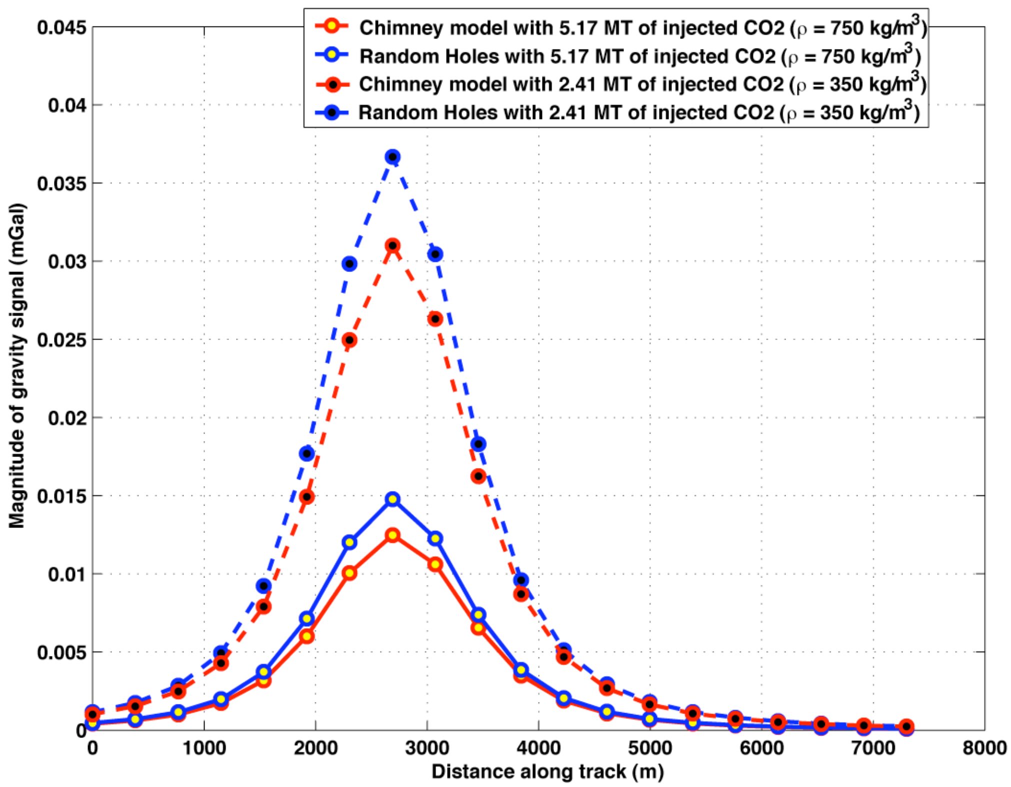


**Figure 6: This shows the time-lapse gravity changes for a high density and a low-density scenario, as calculated from the reservoir simulation models provided by SINTEF. Two model geometries were calculated (Fig. 5): a central chimney geometry and a random holes geometry.**

Further information about the geometry of the $CO_2$ bubble can be extracted by comparing the seismically observed velocity pushdown with the pushdown estimated from the gravity models. To do this, we first constructed a volume containing the seismically imaged layers (Figure 7), then we calculated the pushdown effect assuming that the $CO_2$ was distributed evenly throughout the volume. The seismic velocity is given by the Gassman equation, which is shown in Figure 8. We are working on refining the calculations from the models, but some preliminary results are shown in Figure 9. These indicate that the low-density scenario over-predicts the pushdown and the high-density scenario under-predicts the pushdown. The results also indicate that instead of a uniform distribution of $CO_2$ within the volume, the gas is concentrated more in central region (Figure 8).

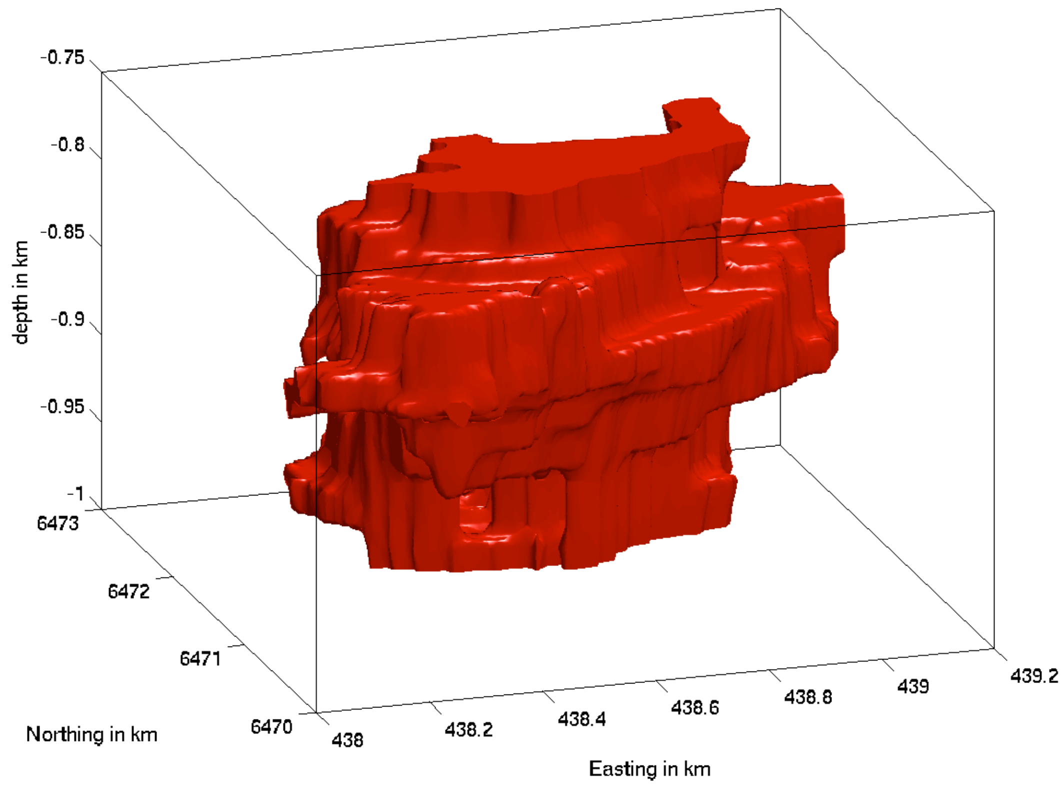


**Figure 7: This figure shows the volume enclosing the seismically imaged horizons. $CO_2$ uniformly distributed within this volume was used to model the gravity and seismic velocity pushdown.**

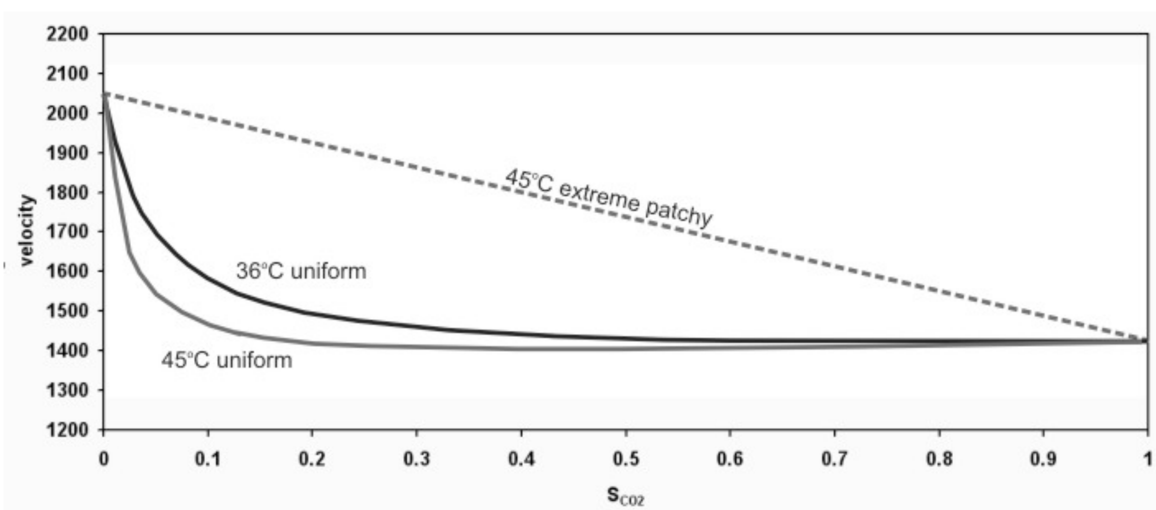


**Figure 8: This figure shows the seismic velocity as a function of $CO_2$ saturation based on the Gassman equation. From saturation values of ~0.2 to 1 the seismic velocity changes by only a small amount.**

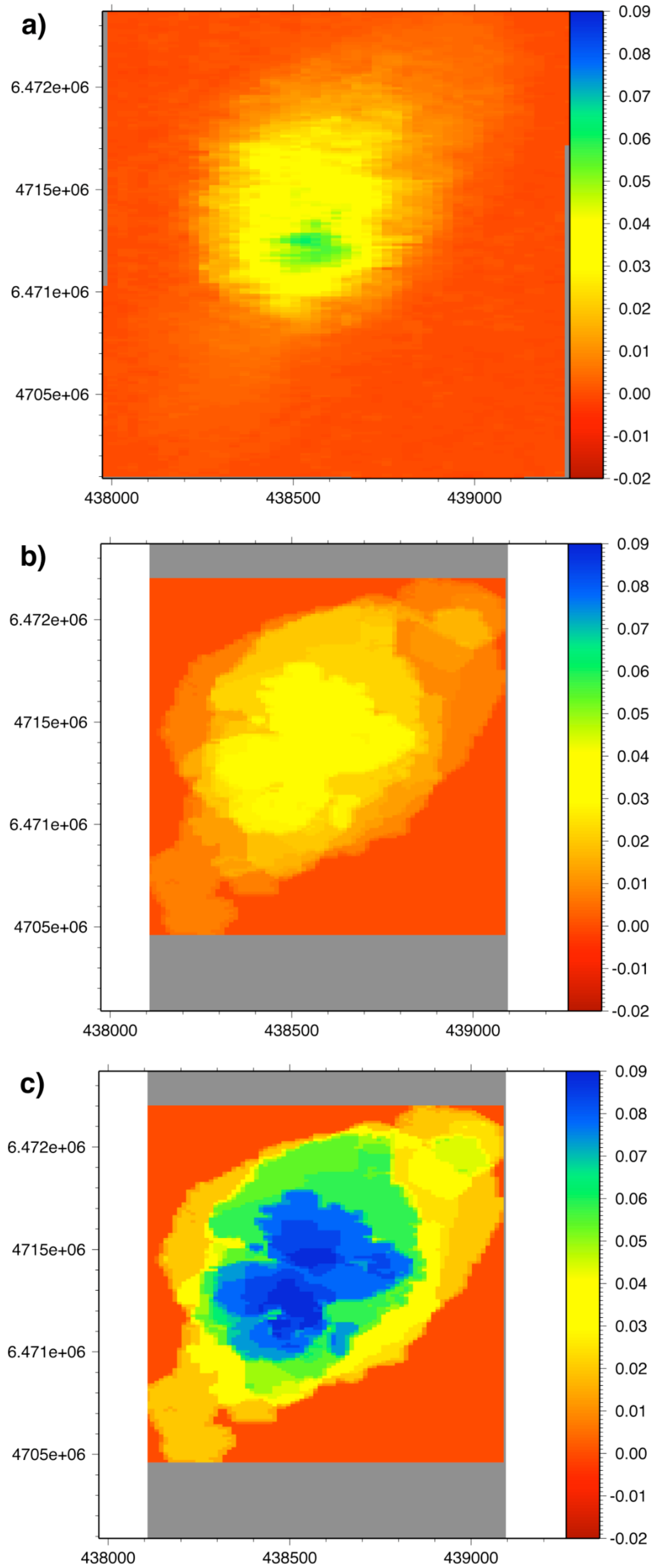


**Figure 9: This figure compares the 2001 seismically observed pushdown (a) to the pushdown predicted by the gravity models based on the seismic horizons. (b) shows the high-density scenario and (c) shows the low-density scenario.**

***Depth Modeling***

Time-lapse seawater pressure measurements made on seafloor benchmarks can be converted to seafloor depth and used to monitor deformation of the seafloor. We did mechanical modeling of the $CO_2$ bubble using two techniques in order to place bounds on the expected uplift due to $CO_2$ injection. The first method approximates the $CO_2$ within the reservoir as a penny shaped pressurized crack. Our calculations were based on a semi-analytical solution from Fialko et al. (2001). The pressure of the $CO_2$ was taken as the buoyancy pressure. The volume of $CO_2$ was taken as a disc with a 1.5 km radius with a mass of 1 MT. Both high and low-density scenarios were examined. The maximum uplift signal expected comes from the low-density case and is ~0.16 cm/year. Over the three-year span between surveys, this would be about 0.5 cm of uplift, which is at the limit of the resolution of our pressure measurements.

A lower bound on the deformation was estimated by treating the seismically imaged $CO_2$ layers as a series of point inflations sources. The inflation is then computed by summing the results from each individual point source. The point source formulation is given by Mogi (1958). The results of this modeling indicate that we expect a minimum deformation of ~$2 \times 10^{-3}$ cm/yr. This amount of uplift is practically negligible, as it is far below our capabilities to resolve.

**Discussion**

Improvements can be made to the models. For the models based on the seismic horizons, the pushdown effect has not been accounted for. This means that for the central area of each horizon, especially for the lower horizons, the true depth is less than given by our simple travel time to depth conversion. The difference exceeds 10-20 meters in the lower layers (Figure 1). However, the gravity modeling shows that the detailed geometry of the $CO_2$ bubble will not affect our estimate of the $CO_2$ density, indicating that this is not a significant source of concern. There are also very little constraints we can place on the diffuse or low saturation volume of $CO_2$. The seismic velocity varies little for saturation values varying from about 0.2 to 0.8 as shown in Figure 7. In other words, a large range of saturation values can cause the same pushdown effect. There is also no rigorous way to define the boundary and shape of the diffuse volume. Another source of ambiguity is the $CO_2$ chimney. It is difficult to define the shape, size, and saturation of the chimney. When the thickness of $CO_2$ exceeds the tuning thickness (~8 m), a loss of increased reflectivity occurs, obscuring the detailed shape of the chimney. We are thinking of ways to model the chimney to try to isolate the affect it may have on the time-lapse gravity.

A problem with the simulation models is that contain the correct injection mass, but they do not reproduce the seismic layering accurately. The gravity modeling of the reservoir simulation models shows that the maximum change in gravity will not be very dependent on the detailed geometry of the $CO_2$ within the reservoir. It also indicates that over time, information on the structure of the bubble will be contained in the shape of the gravity anomaly.

If uplift of the seafloor is observed from our pressure measurements, it will provide us with another independent way to estimate the mass and the density of the $CO_2$

contained within the reservoir. However, the range of deformation expected (2 x $10^{-3}$ to 0.16 cm/yr) suggests that this technique won't be useful until more time has past, at best.

**Conclusions**

The baseline seafloor gravity survey at the Sleipner $CO_2$ sequestration site was very successful. The estimated station uncertainty of 2.5 μGal is significantly better than the 10 μGal accuracy envisioned in Williamson et al. (2001). A follow up survey with similar accuracy will allow us to detect a 5 μGal gravity change.

Williamson et al. (2001) modeled gravity changes arising from various scenarios of $CO_2$ in-situ densities and spatial distributions. In the worst-case scenario (high $CO_2$ density), the maximum gravity change expected would be about 5 μGal/year. Our modeling, based on the 2001 seismically imaged $CO_2$ horizons, indicate even smaller signals (6 μGal/year and 2 μGal/year for 350 kg/$m^3$ and 700 kg/$m^3$, respectively). Gravity predictions from reservoir simulation models suggest similar results for the high-density scenario, but a larger signal for the low-density scenario (7-9 μGal/year and 2-3 μGal/year for 350 kg/$m^3$ and 700 kg/$m^3$, respectively). A repeat gravity survey has been planned for summer 2005. The highly accurate seafloor depth measurements (<0.5 cm) open possibilities of detecting small vertical seafloor movements above the $CO_2$ plume.

The ongoing modeling of the baseline gravity measurements will provide an estimate of the $CO_2$ density and mass. The results of time-lapse surveys will be an independent (and perhaps better constrained) check of this. Models that explore lateral spreading of the carbon dioxide, based on time-lapse seismic data and reservoir simulation models, are also being explored. Our modeling efforts have been undertaken using in-house developed 3-D modeling software. Comparison with analytic solutions has proven our code's reliability and more than adequate precision for the geometry at Sleipner.

In addition to modeling and code-writing progress, we have been successful at interacting with the sequestration community by participating in a number of conferences and meetings. On March 29, 2004, we participated in the 2004 Carbon Sequestration Project Review Meeting for the Department of Energy in Pittsburgh, PA. During the week of May 2, 2004, we attended and presented at the Third Annual Conference on Carbon Capture and Sequestration in Alexandria, VA. A paper is published in the conference proceedings (Nooner et al., 2004). Finally, during the week of August 8, 2004, we took part in the U.S.-Norway, $CO_2$ Summer School in Santa Fe, NM.

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