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 9/19/03 to 3/18/04. During this time, significant advancement in the 3-D gravity forward modeling code was made. Testing of the numerical accuracy of the code was undertaken using both a sheet of mass and a frustum of a cone for test cases. These were chosen because of our ability to do an analytic calculation of gravity for comparison. Tests were also done to determine the feasibility of using point mass approximations rather than cuboids for the forward modeling code. After determining that the point mass approximation is sufficient (and over six times faster computationally), several CO_2 models were constructed and the time-lapse gravity signal was calculated from each. From these models, we expect to see a gravity change ranging from 3-16 μGal/year, depending on reservoir conditions and CO_2 geometry. While more detailed modeling needs to be completed, these initial results show that we may be able to learn a great deal about the state of the CO_2 from the time-lapse gravity results. Also, in December of 2003, we presented at the annual AGU meeting in San Francisco.

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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 15th to the 21st 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. Initial modeling, done by making simple Bouguer corrections to the seafloor gravity data, show that detailed models of local geologic features in the surrounding strata are needed to back out the signal of the injected CO_2.

Thus, further modeling based on updated seismic results, borehole measurements, and seafloor bathymetry is underway. 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.

After looking at commercially available 3-D gravity modeling software, we determined that to accomplish the objectives of this project, we needed to write our own modeling software. We were guided by the need to calculate gravity for an arbitrary shape with a horizontally and vertically varying density. Significant progress towards this end has been made. Based on the estimated gravity change for a range of models, we expect to see a gravity change ranging from 3-16 μGal/year, depending on reservoir conditions and CO_2 geometry. We tested the numerical accuracy of the code by examining a sheet of mass and a frustum of a cone, since gravity from these two shapes can be calculated analytically. In the case of gridded volume data (such as the reservoir simulation models from SINTEF—the largest independent research organization in Scandanavia, www.sintef.no) we compared code that computes the gravity from a cuboid at each grid point with code that computes the gravity from a point mass at each grid point. As expected, the error in the point mass approximation falls off as $e^{-2\pi z/\lambda}$, where z is the distance above the mass and λ is the horizontal grid spacing. For the reservoir simulation models $z \approx 700$ m and $\lambda \approx 12.5$ m, making the error fall of by a factor of about 1.5×10^{-153}. Using point masses results in computation times that are more than 6 times less than using the cuboid code. Therefore, for this case, we prefer to use the point mass approximation to calculate gravity from the CO_2 within Utsira.

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 gravity record.

The primary sensor in the ROVDOG instrument is a modified Scintrex CG-3M gravimeter mounted in a compact gimbal platform for leveling and enclosed in a watertight pressure case. A pressure gauge (Paroscientific 31K) was also housed in each pressure case, and altogether 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.

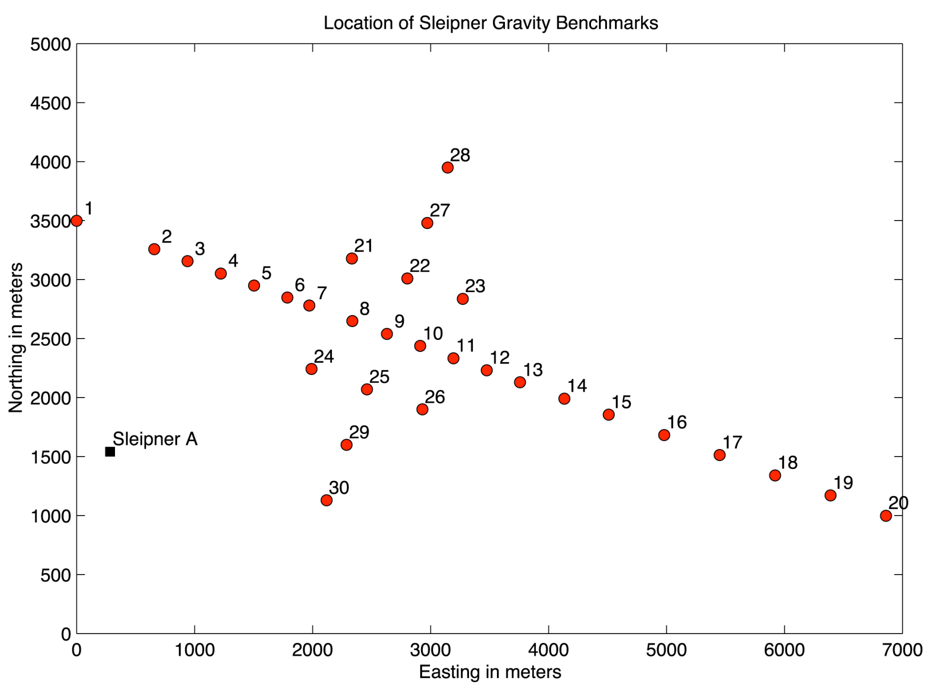


Figure 2. Sleipner gravity benchmark locations are shown in red.

Figure 3: Survey vessel Edda Freya

Figure 4: ROV and gravimeter during recovery.

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.

The next step to take was to use either commercially available 3-D gravity modeling software or in-house developed software to compute the expected time-lapse gravity signal for a range of scenarios. After investigating and testing the commercial software, we realized that we needed to write our own code to do the 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. The code development and modeling results based on this code are both discussed in the next section.

Results

Gravity Modeling Code

We chose two possible methods for our 3-D gravity modeling sofware: building the mass out of a collection of either cuboids or point masses. The gravitational attraction from a cuboid can be calculated analytically, but requires the calculation of 24 terms involving arctangents or logarithms. The derivation of the solution follows Nagy, 1966, except that arctangents are used instead of arcsines (Plouff, D., 1976). The resulting gravity due to a single cuboid is as follows:

$$g_z = G\rho\sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{k=1}^{2}\mu_{ijk}\left[z_k \arctan\frac{x_i y_i}{z_k R_{ijk}} - x_i \log(R_{ijk} + y_i) - y_j \log(R_{ijk} + x_i)\right],$$

where

$$R_{ijk} = \sqrt{x_i^2 + y_j^2 + z_k^2},$$
$$\mu_{ijk} = (-1)^i(-1)^j(-1)^k.$$

G is the gravitational constant, ρ is the density of the cuboid, and x, y, z are coordinates for the cuboid vertices with respect to the observer. The use of arctangents rather than arcsines was chosen because with arcsines the block directly below the observation point must be split into four smaller cuboids, otherwise there are singularities in the calculation. With a large number of observation points, this starts to become cumbersome.

The point mass approximation speeds up the calculation dramatically. The formulation for calculating the gravitational attraction of a point mass is as follows:

$$g_z = \frac{GM}{r^2}\cos\theta = \frac{GMz}{r^3},$$

which is a much faster calculation. (Note: in the above equation, M is the mass of the point mass, r is the distance from the point mass to the observer, and θ is the angle shown in Figure 5.) However, this formulation introduces errors into the calculation because the mass in each cubical element is treated as if it were concentrated at a point in the center. It can be shown that these errors fall off as $e^{-2\pi z/\lambda}$, where z is the distance above the mass and λ is the horizontal grid spacing. For the reservoir simulation models $z \approx 700$ m and $\lambda \approx 12.5$ m, making the error fall of by a factor of about 1.5×10^{-153}. Using point masses results in computation times that are more than 6 times less than using the cuboid code. Therefore, there is no loss of precision in calculating the gravity from reservoir simulation models using the point mass approximation.

Both methods were used to compute the vertical component of the attraction of a mass in the shape of a thin sheet and a mass in the shape of a frustum of a cone. For the case of a thin sheet, if the sheet is made large enough, it approximates an infinite sheet. The analytic solution for an infinite sheet of mass is $g = 2\pi G\rho h$, where h is the thickness of the sheet. This was compared to the values obtained using cuboids and point masses. As expected, the cuboid code yielded results that duplicated the analytical solution when the horizontal extent of the sheet was made large enough. The point mass code also yielded results close to the analytic solution, however large discrepancies were seen whenever the observation point was close to the surface. (In this case, close to the surface means $z/\lambda > 1$.) Additional testing was done comparing the two codes to the analytic solution of the gravitational attraction of a frustum, which is shown below:

$$g_z = 2\pi G\rho h[1 - \cos\theta],$$

where h is the height of the frustum and θ is the angle shown in Figure 5. This analytic solution is valid only at the point centered above the frustum and located at $z = r\tan\theta$, where r is the radius of the frustum base (Figure 5). This geometry provides a way to look at a complex shape at a point arbitrarily far from the surface (depending on the geometry chosen). Figure 6a shows the actual frustum shape overlaying the same frustum composed of cuboids. Figure 6b shows the same with point masses. As the grid size decreases, the results of each code approach the analytic solution (Figure 7) at the same rate. (Note: The geometry was chosen so that the size of the frustum and the height of the observation points are similar to the situation we have at Sleipner.)

Based on these results, we can safely conclude the following: 1. Our in-house developed code based on cuboids or point masses are working correctly. 2. With the grid sizes and geometry at Sleipner, we expect the numerical error in the modelling code to be much less than the observable gravity signal. 3. Also due to the geometry at Sleipner, we can use the faster point mass code for time-lapse gravity modeling.

Gravity Modeling Results

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 8). 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 vertical CO_2 ‘chimney’ (modeled as a cylinder) and in a low saturation sphere centered on the seismically imaged volume. 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 8).

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 (ρ_{co_2} = 700 kg/m^3) scenario and a low CO_2 density (ρ_{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.

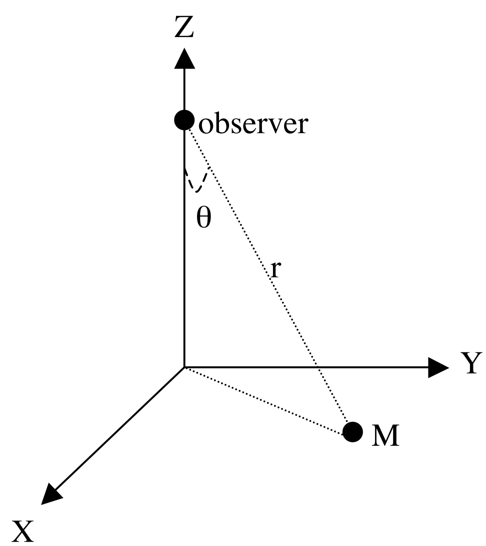
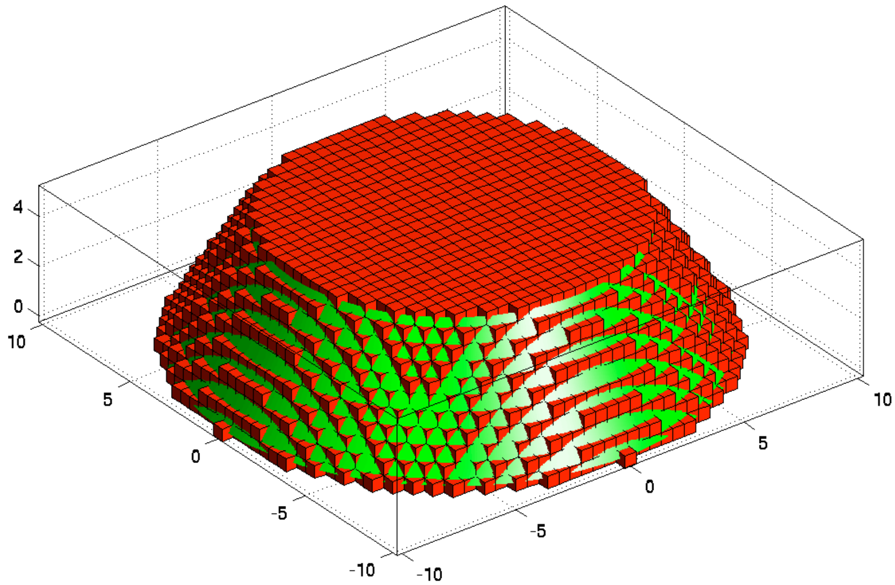


Figure 5: This figure shows the coordinate system used for the gravity modelling.



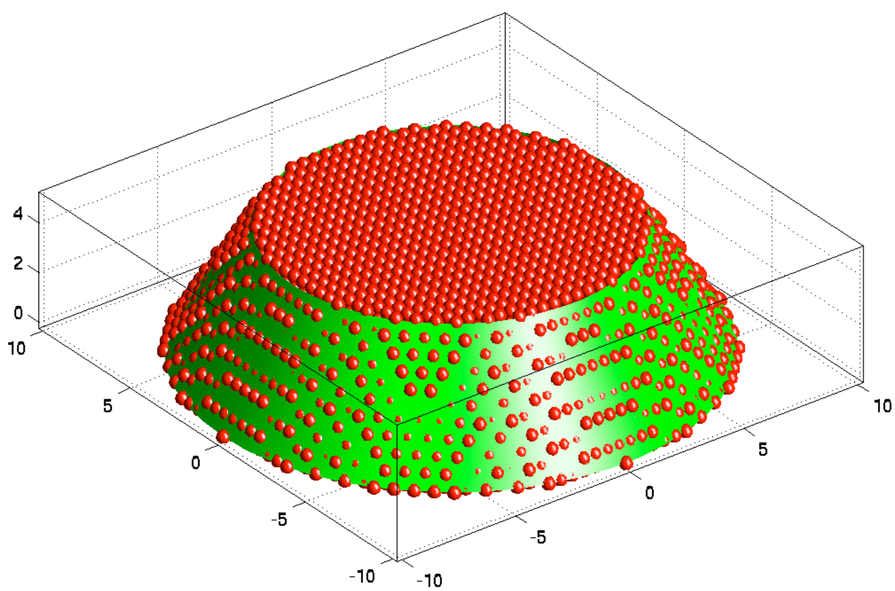


Figure 6: A). The top figure shows the cuboid approximation to a frustum (red) overlain by the real thing (green). B). The bottom shown the same for spheres (or point masses).

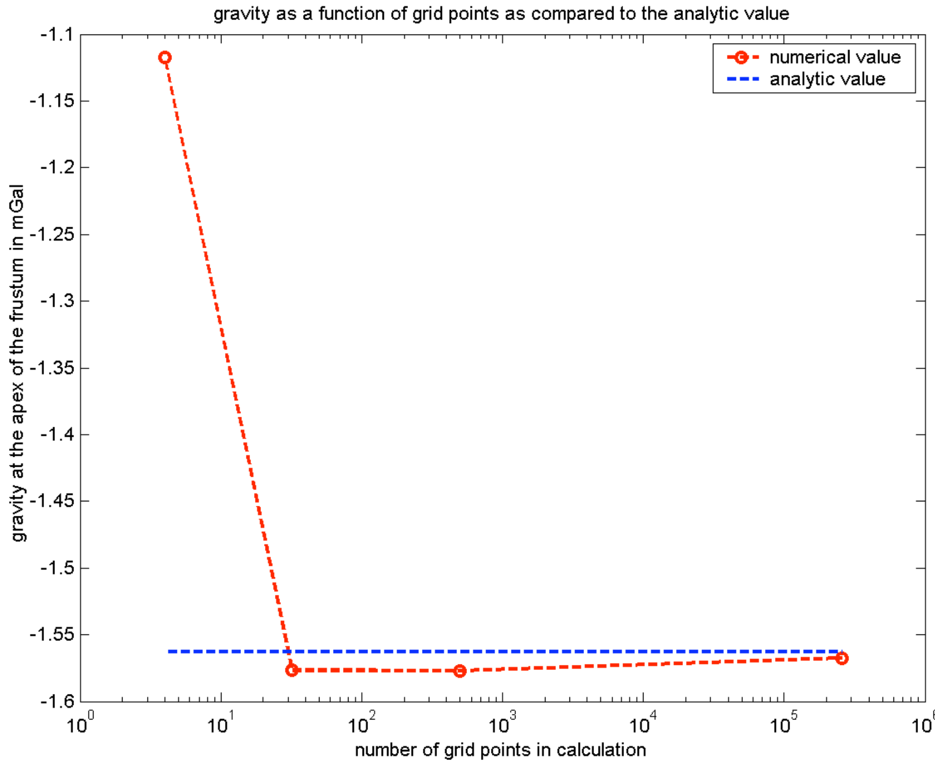


Figure 7: This shows that the numerically calculated value from the code approaches the analytic value as the number of grid points making up the frustum increases.

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 8a). 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 8b). 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. We did this by assuming the CO_2 flow would not change if density of CO_2 changes. We assumed that the volume of the CO_2 was the same, but the mass and the density decreased. This assumption is most like not true, however, we wanted to get some feel for the size of gravity change suggested by the lower density scenario. 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 13-15 μGal/year. For the high-density case, this is about the same as for the seismic horizon model, however, for the low-density case, these results are about twice what is predicted by the seismic horizon model.

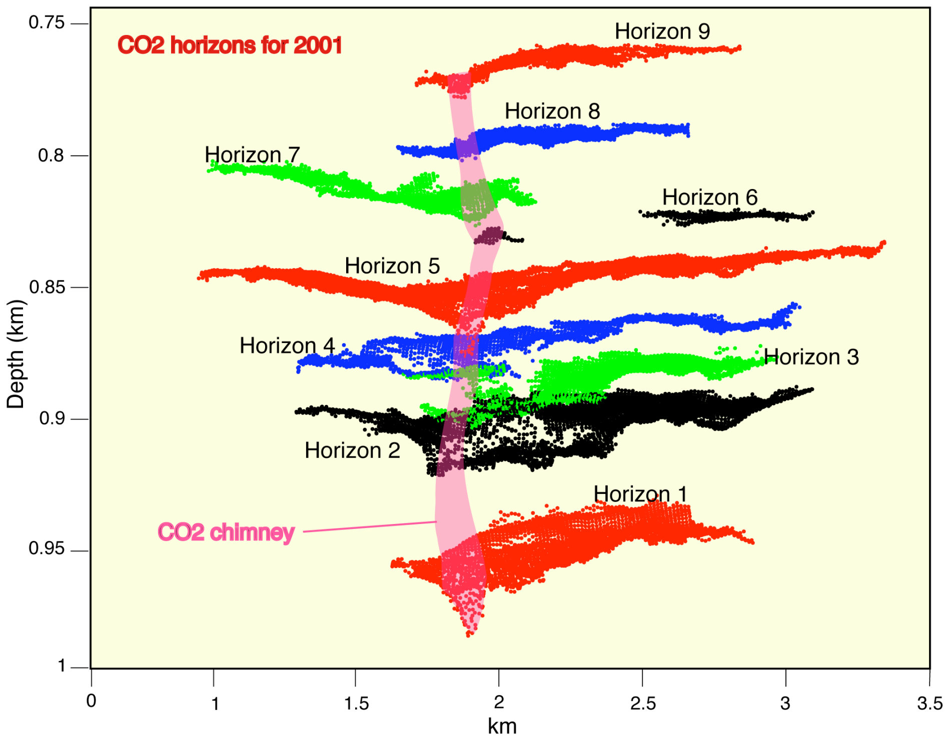


Figure 8: This shows a side-view of the seismically imaged CO_2 horizons. The seismic pushdown in the layers can be seen. The chimney that is drawn in is for illustration only.

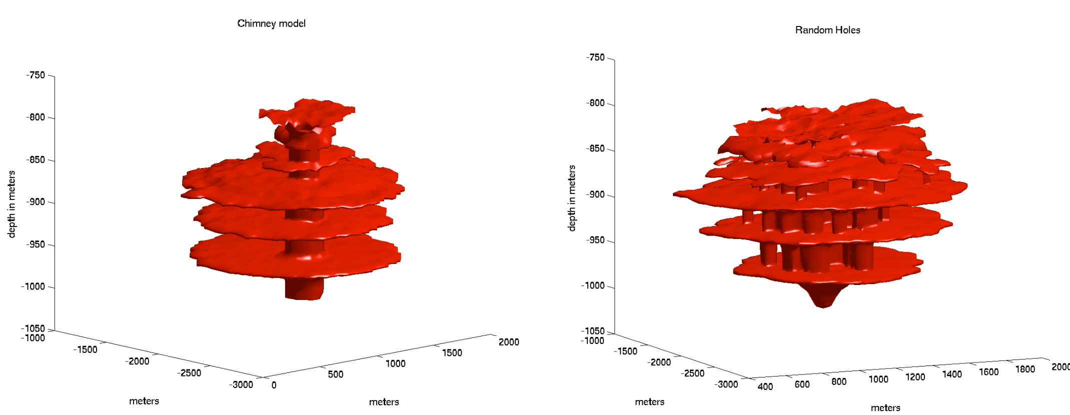


Figure 9: A). The figure on the left shows the single chimney model from the reservoir simulations. There is not diffuse volume of CO_2. B). The figure on the right shows the reservoir simulation model which uses several micro-chimneys to create a situation that might affect the seismic pushdown without needing a diffuse volume of CO_2.

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 7). We are working on this problem. 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. 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 of the diffuse volume. We are working on models with different saturation volume boundaries and saturations in order to see the effect this quantity of CO_2 might have on the time-lapse gravity. 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.

For the reservoir simulation models, we are trying to obtain a more complete picture of the change in gravity over time. We have asked SINTEF to send us the simulation model results for a number of steps through time. We have also asked them to run some simulations using a lower density value for the CO_2. This should help to clear up uncertainties we have about the low-density case. A problem with the simulation models is that they do not reproduce the seismic layering accurately. Therefore, there may be small differences in the gravity results from the models and the gravity results from the actual measurements.

These issues outstanding, we can still make some informative observations from the modeling thus far. We can see that the high-density scenario shows very little sensitivity to the detailed geometry of the CO_2 flow (2 μGal/year for the seismic horizons verses 2-3 μGal/year for the reservoir simulation models). The low-density scenario, however, appears to be very sensitive to the details of the geometry (6 μGal/year for the seismic horizons verses 13-15 μGal/year for the reservoir simulation models). We can also speculate that in future years, the shape of the seafloor gravity signature may tell us information about the geometry of the CO_2, such as saturation of the chimney, for example.

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 (13-15 μGal/year and 2-3 μGal/year for 350 kg/m^3 and 700 kg/m^3, respectively). A repeat gravity survey is tentatively on schedule for late 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.

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