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

Semi-Annual Technical Progress Report

Reporting Period: 3/19/03 - 9/18/03

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Report Issued: 11/17/03

DOE Award Number: DE-FC26-02NT41587

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 three-week trip to Statoil Research Centre in Trondheim, Norway, was made in the summer of 2003. This visit consisted of gathering data and collaborating with scientists working on the Sleipner project. The trip ended with a presentation of the seafloor gravity results to date at a SACS2 (Saline Aquifer CO_2 Storage 2) meeting. This meeting provided the perfect opportunity to meet and gather information from the world's experts on the Sleipner project.

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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. 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.

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 null level, 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 modelling, 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 modelling 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.

Scott Nooner visited the Statoil Research Center in Trondheim, Norway from August 25th until September 12th, 2003. During his visit, he met with Statoil scientists with expertise in the Sleipner area and gathered the available data for the region. He also did some gravity modelling using a model directly interpreted from the 4-D seismics. At the end of the visit, Mark Zumberge and Scott Nooner attended a Sleipner CO2STORE geophysical/reservoir engineering meeting in Trondheim, on September 9-10. At this meeting, the gravity modelling results were presented and tentative plans for a repeat gravity survey in 2005 were made.

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 μGals, 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 on the gravity meters 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.

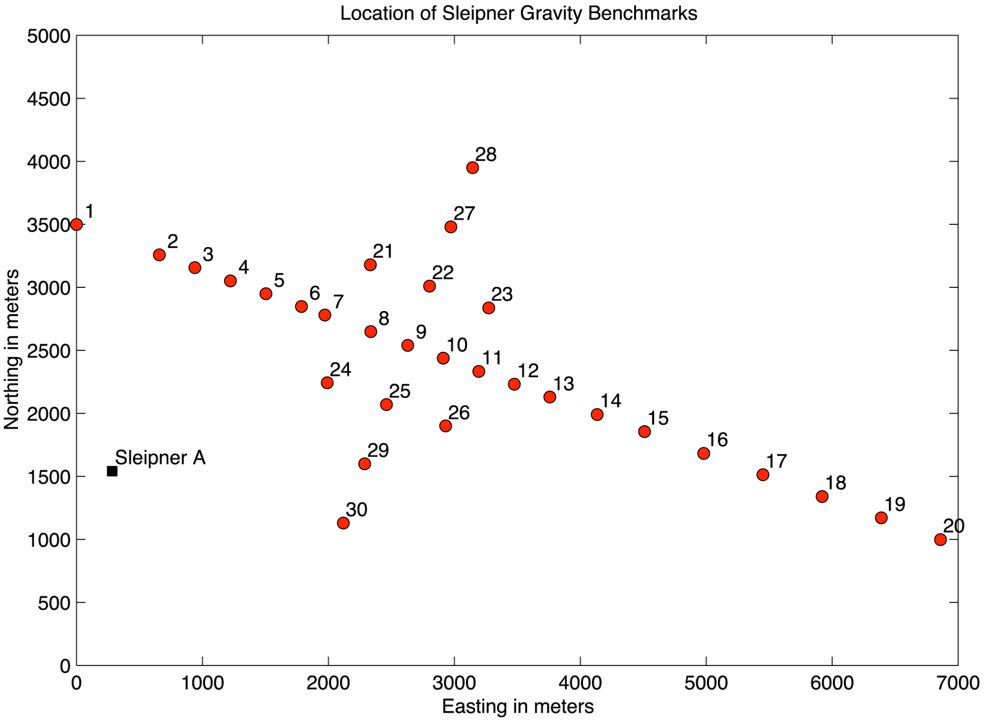

Figure 2. Sleipner gravity benchmark locations are shown in red.

Figure 3: Survey vessel Edda Freya

Figure 4: ROV and gravimeter during recovery.

Marine operations

The supply vessel *Edda Freya* which has been converted for ROV/Subsea operations was used for the survey (Figure 3). The vessel carries a HIROV 3000 Mk II (Figure 4), which is a work class ROV equipped with a 5-function arm and a 7-function manipulator arm. The ROV is launched and recovered with an A-frame on the side of the ship.

The gravity measurements were made from the 16th of August, 2002, until the 20th of August. 115 measurements were made in total, which amounts to about 30 per day. Survey loops of about 7 hours were made with station #9 as the central location. This site was visited 15 times during the four days. All other stations had at least 3 occupations, and the easternmost station (#20), received five visits. This is because it is thought to be well outside the area of CO_2 influence, so will serve as a reference location for future gravity changes.

Further Data Acquisition

Travel to Statoil Research Center

Scott Nooner, a graduate student, spent about three weeks at the Statoil Research Center in Trondheim, Norway from August 25th until September 12th, 2003. The cost of lodging and flights were covered by Statoil, and food expenses were taken from this grant. During this time, Scott met Statoil scientists with expertise in the Sleipner area. He was able to obtain the pre-injection seismic data, density log data from nearby wells, shipborne gravity data of the area, and bathymetry. These data sets provide the framework needed to build a subsurface density model, which will be used to attempt to extract a CO_2 signature from the first year's data.

Scott also obtained the post-injection 4-D seismic data for 1999, 2001, and 2002 (the last corresponding to the year of the gravity survey), and daily injection rate data. The time-lapse difference of these data sets shows the existence of at least nine CO_2 horizons. Evidence of these horizons is seen in both a difference in reflection amplitude and by a velocity pushdown effect. The velocity pushdown is caused by decreased seismic velocities through the less dense carbon dioxide. The data is not currently available to the public. The seismic horizons are interpreted as CO_2 ponding on thin shale layers that laterally cut the Utsira sand, but are not visible in the pre-injection seismic data. He built a gravity model based on the 4-D seismics, which is discussed in the next section.

At the end of this three-week visit to Norway, a SACS project geophysical/reservoir engineering meeting was held in Trondheim. Both Scott Nooner and Mark Zumberge attended. The meeting was a gathering of the world's experts on the Sleipner CO_2 sequestration. About 14 geophysicists, geologists, hydrologists, and reservoir engineers gathered to discuss the current work and the future plans for the project. A presentation including a summary of the seafloor gravity acquisition and gravity modelling and predictions was given at the meeting. It was determined that a repeat gravity survey is a high priority, in order to quantify the density of CO_2 within the reservoir. A repeat survey was tentatively planned for 2005. We have also obtained the current reservoir simulation models and are in the process of writing code to calculate the expected gravity directly from them.

Results and Discussion

Depth estimates

Processing of depth time series was done in collaboration with Ola Eiken and Torkjell Stenvold at Statoil using in-house developed Matlab code. The mean pressure from the three sensors was converted to a depth at each site. The depths range from 79.5 m to 83.6 m. For monitoring relative changes, depths are referenced to locations outside the area of gas injection, such as station #20. Agreements of station repeats are shown in

Figure 5. The standard deviation is 0.5 cm. Apart from three outliers, all values are within 0.8 cm.

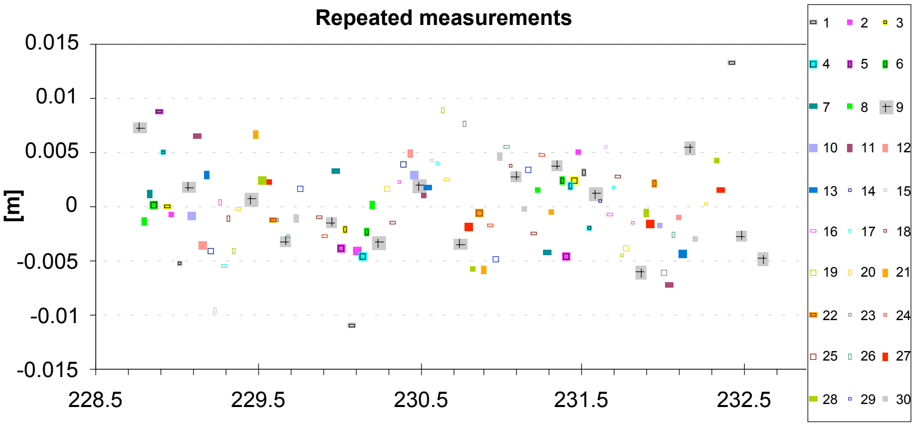

Figure 5: Deviations from station means plotted verses day number. The repeatability is 0.5 cm.

Gravity estimates

Processing of the gravity data was also done in collaboration with Statoil colleagues Ola Eiken, Torkjell Stenvold, and Håvard Alnes. The quality of the data is evident in the repeatability of the measurements. Quality control was thus done by comparing repeated observations in three ways: 1. Multiple measurements made at each benchmark were compared. 2. Agreement among the three meters was examined for each measurement. 3. Stability of each measurement was examined by comparing the first and second half of each 20 minute gravity record.

Visco-elastic relaxation of the quartz springs in the gravimeters causes recovery effects. The size of this effect seen by comparing the mean of the first half and second half of a 20 minute record is –2.3 μGal on average. Each gravity measurement was about 20 minutes long. This is long enough for this transient effect to pass, as well as reduce the noise from microseisms to acceptable levels.

The gravity values were corrected for solid earth tides and ocean loading using a world-wide tidal model (Agnew, 1996). Sea level height estimates based on reference pressures allowed us to correct the data for imperfections in the tidal model. Instrument drift for each gravimeter was estimated by minimizing the residuals of all repeat measurements in a least squares sense. The first and second order drift terms used for each of the three gravimeters (U1, U2, and U3) are shown in Table 1. Units 2 and 3 had different drift rates in the beginning of the survey than at the end. This is also shown in Table 1.

	Linear term [mGal/day]		2nd Order term [mGal/day²]		Split time
	1st Half	2nd Half	1st Half	2nd Half	
U1	0.55648		-0.001704		
U2	0.36277	0.44239	0	-.000103	229.7
U3	0.17792	0.19274	-.030647	0.000598	229.8

Table 1: Drift coefficients for the three gravity sensors.

The repeatability of the units are 8.8 μGal, 9.9 μGal, and 4.7 μGal for U1, U2, and U3 respectively. Because of the much better performance of U3, the data from this meter was heavily weighted when averaging the three units. After weights of 0.396 (U1), 0.264 (U2) and 2.261 (U3) were used, the repeatability for a single gravimeter is 4.3 μGal (Figure 6). However, if the remaining error sources are random, station repeatability for all three meters taken together should be about 2.5 μGal (4.3 μGal/sqrt(3)). For time-lapse changes, additional uncertainty is related to determining the reference zero-level, which is obtained from stations outside the area of influence of the CO_2 injection. For example, the primary reference station, # 20, was occupied five times with a repeatability of 1.9 μGal. This error will add to all stations.

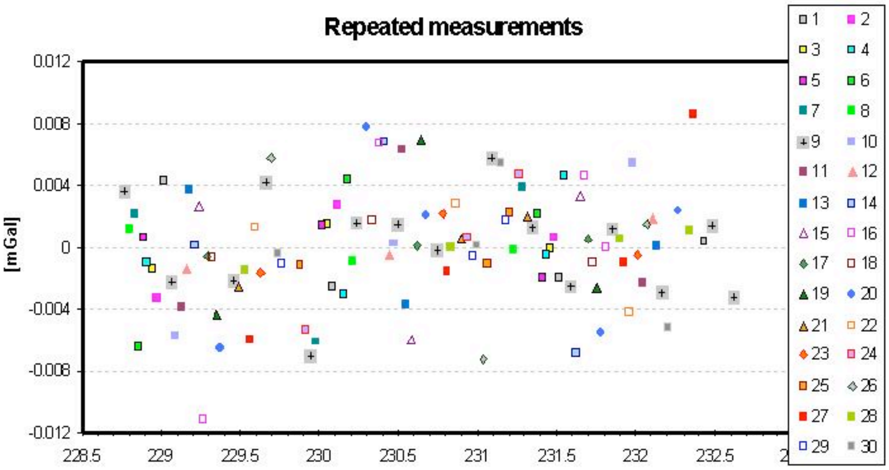

Figure 6: Repeatability for weighted unit averaged measurements plotted verses day number. Standard deviation is 4.3 μGal. Different symbols denote different stations in the survey network.

Gravity Modelling

We can obtain a good estimate of the expected time-lapse peak gravity signal on the seafloor using a very simple model to demonstrate the effect (Figure 7). In this

picture, the CO_2 forms a sphere of radius *r*, centered at depth *d*. The top of the sphere is constrained by the shale caprock at 800 m bsl. As more CO_2 is injected into the formation, the volume of the sphere increases, but the top of the sphere remains fixed. Figure 8 shows the peak gravity change as a function of CO_2 density for 100% saturation. The formulation is as follows:
In general the volume that the CO_2 occupies, *V*, is given by

$$V\phi(1-\nu_{sh})S=\frac{M_{CO_2}}{\rho_{CO_2}}=\frac{M_w}{\rho_w} \qquad \text{----(1)}$$

where ρ_{CO_2}, M_{CO_2}, and ϕ are CO_2 density, injected mass, and rock porosity, respectively. S is the CO_2 saturation and ν_{sh} is the fractional percent of shale in the formation by volume. Therefore,

$$\Delta M=M_{CO_2}\left(1-\frac{\rho_w}{\rho_{CO_2}}\right). \qquad \text{----(2)}$$

For our geometry (Figure 3),

$$\Delta g=\frac{G\Delta M}{R^2}. \qquad \text{----(3)}$$

$V=\frac{4}{3}\pi r^3$ for a sphere, so

$$R=(z+r)=\left[z+\left(\frac{3M_{CO_2}}{4\pi\phi(1-\nu_{sh})S\rho_{CO_2}}\right)^{1/3}\right]. \qquad \text{----(4)}$$

From this it follows that

$$\Delta g=\frac{GM_{CO_2}\left(1-\dfrac{\rho_w}{\rho_{CO_2}}\right)}{\left[z+\left(\dfrac{3M_{CO_2}}{4\pi\phi(1-\nu_{sh})S\rho_{CO_2}}\right)^{1/3}\right]^2}. \qquad \text{----(5)}$$

For the calculation we used $\phi = 0.37$, $S = 1$, and $\nu_{sh} = 0.15$. These values for ϕ and ν_{sh} were estimated from tests on core samples (SACS final report, 2000). 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. Figure 9 shows CO_2 density with depth for three different temperature profiles to demonstrate this issue. As a simplification, the results of the model were calculated for two density scenarios (350 kg/m^3 and 700 kg/m^3). The results from this show a peak anomaly of -37 μGal for the low-density case and -10 μGal for the high density case after 2.268 MT of injected CO_2 (Figure 8). These results are virtually identical to the more complicated models of Williamson et al. (2001). This simply demonstrates the size of the signal, however. This is useful, though. Because the change in density occurs so quickly, the size of the time-lapse gravity signal should tell us whether the CO_2 is in a high or low-density state.

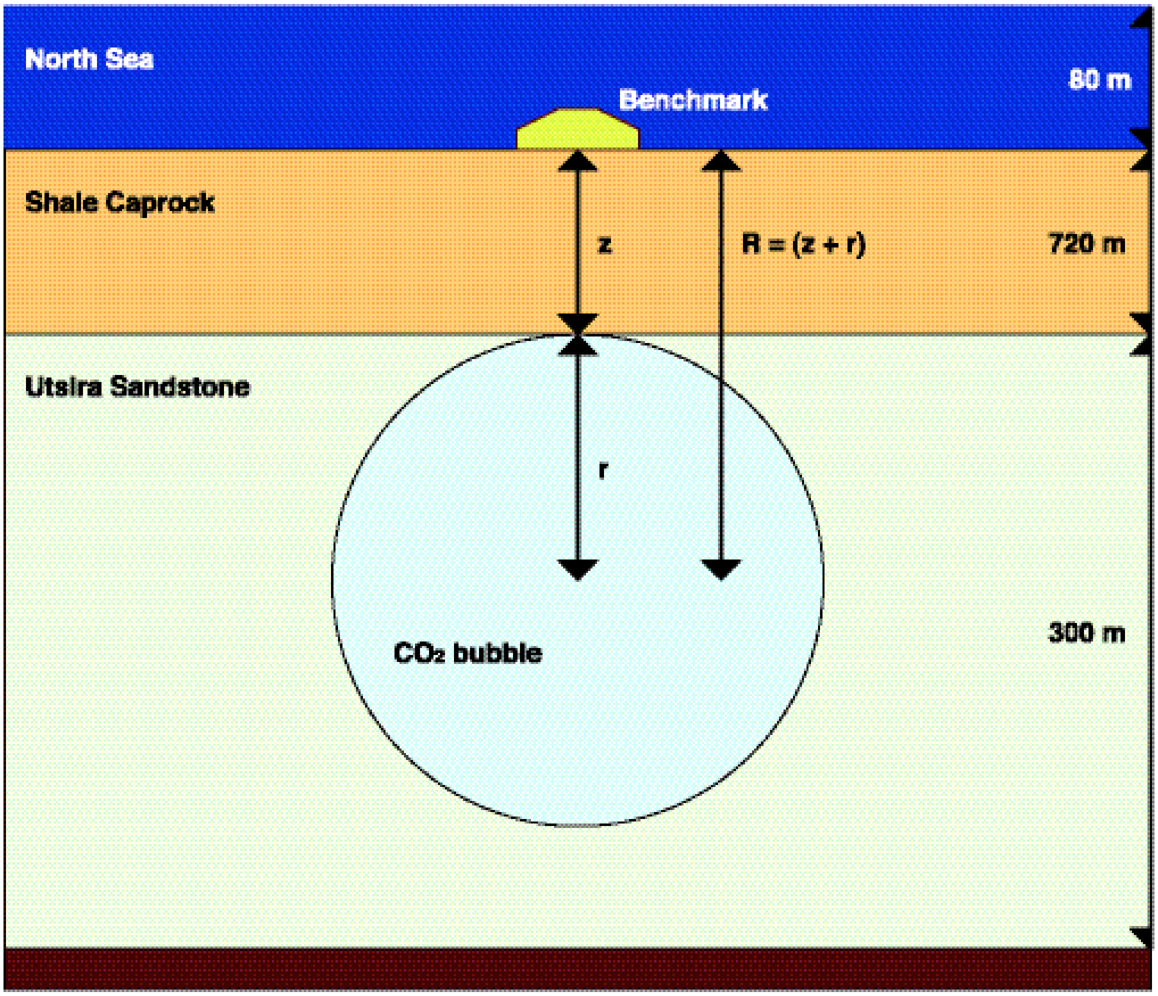

Figure 7: This is a cartoon illustrating the simple spherical model used to estimate the size of the gravity signal on the seafloor. The dimensions are not to scale.

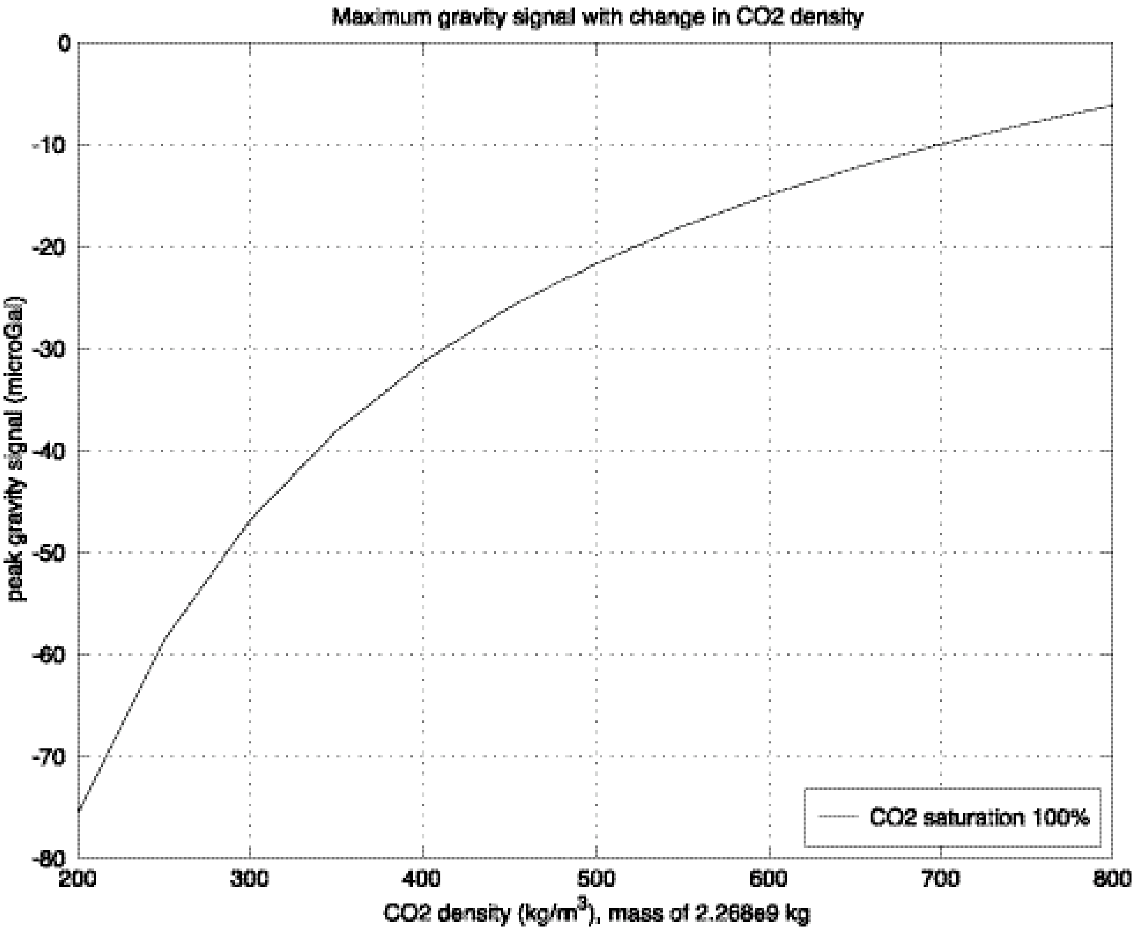

Figure 8: This plot shows the expected peak gravity anomaly after just over two years of CO_2 injection for a range of CO_2 densities. The model volume used in the calculation was a sphere that was bounded on the top by the caprock at 800 m bsl.

In order to accurately estimate the saturation, the parameter needed for seismic estimation of mass, a careful treatment of the CO_2 bubble volume is needed. By inverting Δg while using the seismically determined ΔV as a constraint, we can determine the effective density contrast in the bubble. This is related to CO_2 saturation and density by the following equation:

$$\Delta\rho_{eff} = (\rho_{CO_2} - \rho_w)\phi S(1 - \phi_{sh}). \qquad \text{----(6)}$$

The amplitude of the gravity signal will tell us something about the density regime of the CO_2. Therefore, making appropriate assumptions about ρ_{CO_2}, will give us an estimate for the saturation, S. In the future, once ρ_{CO_2} has been determined, we will be able to directly solve for the change in mass with gravity and seismic volume.

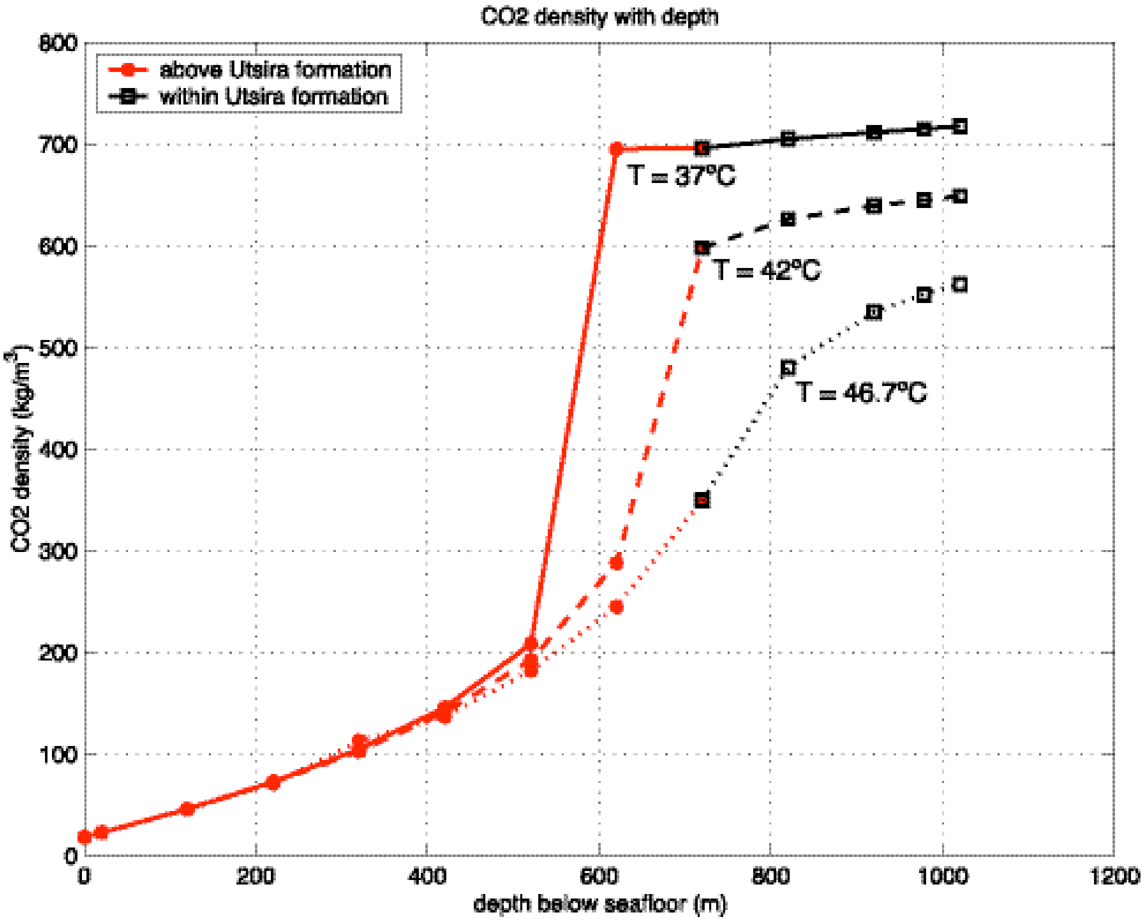

Figure 9: This shows a plot of CO_2 density with depth for three different temperature profiles, based on the uncertainty in the temperature. The black lines show the location of the Utsira formation in each case. Notice the rapid change in density from 200 kg/m^3 to ~700 kg/m^3.

During the trip to the Statoil Research Centre in August/September 2003, another model was built using the seismically imaged CO_2 horizons in both 1999 and 2001 to constrain the volume of the CO_2. The total mass of injected CO_2 was taken to be the known value of injected gas. Gravity was calculated from this model at the locations of the seafloor benchmarks by assuming the seismically imaged bubble contains only carbon dioxide in high saturations (70%) and the remaining carbon dioxide was located in a low saturation spherical volume centered at 850 m depth (centered on the seismically imaged bubble). Layer depth was determined using a linear velocity model, and layer thickness was linearly related to reflection amplitude (Chadwick et al., 2002) with the maximum amplitude corresponding to an 8 m thick layer. Porosity was taken to be 0.37 within the formation (SACS2 final technical report). The change in gravity seen on the seafloor benchmarks in these models depends on the density of CO_2 within the Utsira formation, as discussed above. The maximum change in gravity was seen to be about -30 μGal/year and –5 μGal/year for 350 kg/m^3 and 700 kg/m^3, respectively. This more realistic model confirms that we expect to be able to put limitations on the CO_2 density with time-lapse gravity measurements spanning at least 2 years.

To gleen information about the CO_2 bubble from the a single year of gravity data, detailed information must be known abou the region. The terrain in the Sleipner region is very flat, changing by less than 5 meters over the area of the survey. Therefore, a simple Bouguer correction was done to the data as a preliminary attempt at modelling. A regional gravity signal was also subtracted from the data (Figure 10). However, the resulting gravity anomalies were not consistent with what was expected from our models the CO_2 bubble. This is probably due to unmodelled geologic variation in the local strata. Therefore a better subsurface density model is needed for the region.

In order to build a detailed subsurface density model, pre-injection seismic data, core sample data, well logs, seasurface gravity and bathymetry are needed. This data was obtained from Statoil in August/September 2003. Code is being written that will enable us to use all of these data sets together to build a 3-D subsurface density model of the region and in order to put constrains on the density and mass of the injected CO_2. Building such a model is not a straightforward task. One problem comes from incomplete data coverage. For example, the density logs are from nearby wells, thus give only an average sense of subsurface density variations. The density logs also all lack information about the upper 500 m of the wells. Small-scale gravity variations, however, can be sensitive to density structure in this upper region. Another problem is that while shipboard gravity data can give us a sense of the long wavelength gravity trends in the area, it is about two orders of magnitude less precise than the seafloor data that we have measured. The seismic records are limited in that it can be difficult to separate noisy data from small wavelength reflectors. Work on interpreting this data and building a subsurface density model is underway.

We met reservoir engineers from Scintef at the Trondheim meeting in September, who have since supplied us with the results from their CO_2 saturation and flow models. The models show the results up of 6 years of injections for different CO_2 transport scenarios. We are writing code to allow us to compute the expected seafloor gravity directly from these models. This will be a useful predictive tool in future seafloor surveys. These models also provide us a good way of visualizing the CO_2 bubble in 3-D.

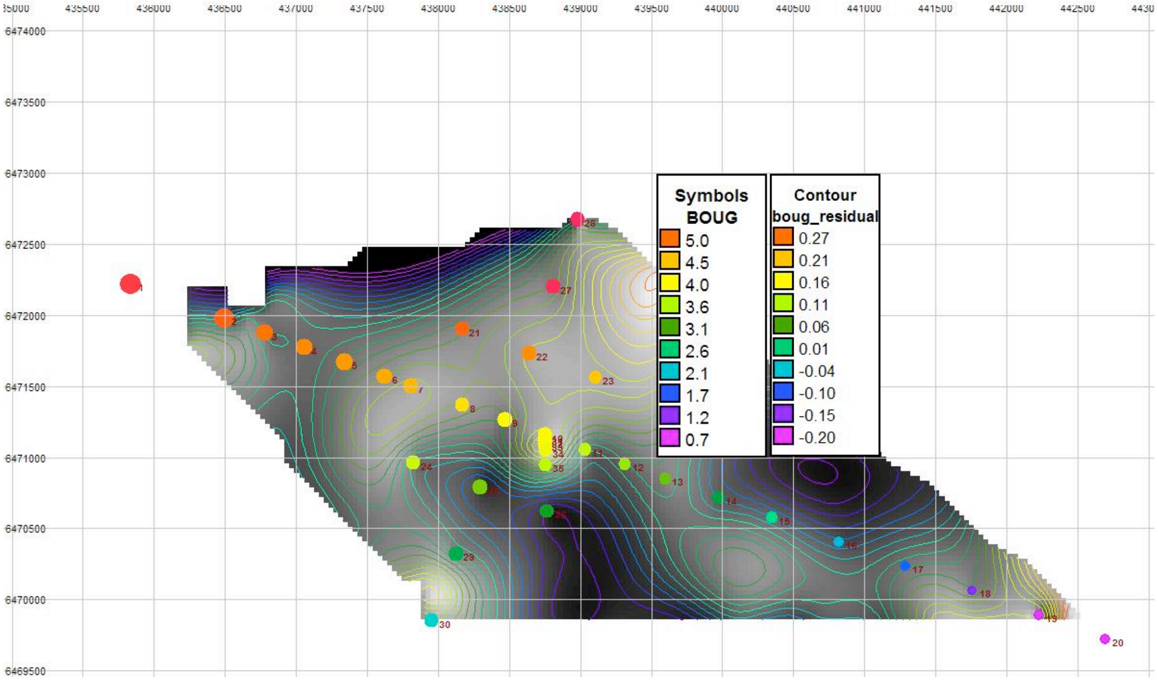

Figure 10. The circles show the benchmark location and the value of the Bouguer anomaly before a residual correction was made. The contours show the value of the anomalies after the subtraction of a regional signal. Note that the contours only have meaning near the location of the benchmarks.

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 for a two year period. In the worst case scenario, the maximum gravity change expected would be about -10 μGal for a two-year period of injection. Our modeling, based on the 2001 seismically imaged CO_2 horizons, indicate similar results (-30 μGal/year and –5 μGal/year for 350 kg/m^3 and 700 kg/m^3, respectively). It is therefore likely that a change in gravity will be detectable in a future survey spanning two years or more. From the SACS meeting in Trondheim from September 9-10, a repeat gravity survey is tentatively on schedule for 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, are also being explored. We plan to continue to work in collaboration with reservoir engineers to calculate the expected gravity change for a range of carbon dioxide flow scenarios.

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