Constraining the density of CO\textsubscript{2} within the Utsira formation using time-lapse gravity measurements

Scott Nooner\textsuperscript{1}, Mark Zumberge\textsuperscript{1}, Ola Eiken\textsuperscript{2}, Torkjell Stenvold\textsuperscript{3}, Sylvain Thibeau\textsuperscript{4}

\textsuperscript{1}Scripps Institution of Oceanography
University of California San Diego
9500 Gilman Dr., La Jolla, CA 92093, USA

\textsuperscript{2}Statoil Research Center
Rotvoll, N-7005 Trondheim, Norway

\textsuperscript{3}The Norwegian University of Science and Technology (NTNU)
NO-7491 Trondheim, Norway

\textsuperscript{4}Total
Avenue Larribau, 64018 Pau Cédex, France

Abstract
At Sleipner, CO\textsubscript{2} is being separated from natural gas and injected into an underground saline aquifer, known as the Utsira formation, for environmental purposes. In this study, gravity measurements were made over the Sleipner CO\textsubscript{2} injection site in 2002 and 2005 on top of 30 concrete benchmarks on the seafloor in order to study the behavior and physical properties of the injected CO\textsubscript{2}. The gravity measurements show a repeatability of 4.3 \(\mu\text{Gal}\) for 2003 and 3.5 \(\mu\text{Gal}\) for 2005. The formal time-lapse uncertainty is 5.3 \(\mu\text{Gal}\), however vertical benchmark motions that are likely due to local sediment scouring, obscure the sought after signal. Forward models of the gravity change are calculated based on both 3-D seismic data and reservoir simulation models from other studies. These forward models indicate that the magnitude of maximum gravity change is primarily related to CO\textsubscript{2} density rather than flow geometry. The time-lapse gravity observations best fit a high temperature forward model based on the seismically determined CO\textsubscript{2} geometry, suggesting that the 3-D reflection seismics are imaging the geometry of the injected CO\textsubscript{2}, and that the \textit{in situ} CO\textsubscript{2} density is around 530 kg/m\textsuperscript{3}. Uncertainty in determining the average density using this technique is estimated to be \(\pm 65\) kg/m\textsuperscript{3} (95\% confidence), however, additional seismic surveys are needed before firm conclusions can be drawn. Future gravity measurements will put better constraints on the CO\textsubscript{2} density and continue to map out the CO\textsubscript{2} flow.

Keywords: CO\textsubscript{2}, seafloor gravity, reservoir monitoring, Sleipner, Utsira, geologic storage

Introduction

The Sleipner Project

The Sleipner Project is the world’s first commercial application of emissions avoidance through the use of carbon capture and geologic storage technologies. The Sleipner field is a natural gas production area located about 240 km off the coast of Norway in the North Sea and operated by Statoil. In order for natural gas drawn from the site to meet commercial specifications, its CO\textsubscript{2} content must be reduced from about 9\% to 2.5\%. In gas fields worldwide, this excess CO\textsubscript{2} is typically vented into the atmosphere, but at Sleipner the CO\textsubscript{2} is compressed and injected into a porous saline aquifer known as the Utsira formation \cite{1, 2}. The injection point is at a depth of 1012 m bsl and the water depth is about 80 m. Injection began in 1996 at a gradually increasing rate. Now, about 1 million tons (MT) of CO\textsubscript{2} are being separated from the natural gas and injected into the Utsira formation each year.

Because CO\textsubscript{2} has never been compressed and injected in to an underground formation for environmental geologic storage, monitoring the injected CO\textsubscript{2} is used to confirm that it is safe and

\textsuperscript{*} Corresponding author: snooner@ucsd.edu 1-858-534-8763
reliable. Time-lapse 3-D seismic surveys have been successfully employed to image the underground CO$_2$ [3, 4]. In this study, we use time-lapse seafloor gravity measurements to image and to put constraints on the in situ density of the CO$_2$.

**In situ mass estimates**

In addition to a pre-injection 3-D seismic survey obtained in 1994, 3-D seismic data were acquired over the Sleipner area in 1999, 2001, and 2002 (partial coverage of the CO$_2$ plume). The results of the seismic surveys clearly show the geometry of the injected CO$_2$ [4]. By 1999, some of the CO$_2$ had reached the top of the Utsira sand and the plume has since been spreading both laterally and upwards from the lower levels towards the top of the formation. High amplitude sub-horizontal reflections are caused by accumulation of CO$_2$ under thin inter-reservoir shale layers [3-5], which act as temporary barriers to buoyantly driven CO$_2$ flow.

Monitoring can be used to quantify the amount of in situ CO$_2$, thereby testing the monitoring techniques, and possibly the storage process in the reservoir. Arts *et al.* [6] and Chadwick *et al.* [5] made estimates of the CO$_2$ mass within the Utsira sand in 1999 using the seismically imaged volume. Assuming the density of CO$_2$ within the reservoir to be 700 kg/m$^3$ Chadwick *et al.* [5] estimated 2.01 MT compared to the known injected mass of 2.35 MT for 1999. In this model the CO$_2$ within the reservoir was partitioned between high saturation thin layers and a low saturation volume existing in a diffuse form between the layers. Evidence supporting the existence of diffuse CO$_2$ is given by Chadwick *et al.* [4]. Mechanisms such as dissolution of CO$_2$ into the formation water can help explain the difference in known injected mass and the estimation by Chadwick *et al.* [5]. However, one of the largest sources of uncertainty in estimates of CO$_2$ mass comes from uncertainty in the density of CO$_2$ within the Utsira formation. The density of CO$_2$ depends primarily on the temperature. The impact of impurities such as methane, BTX (butanes, toluenes, and xylenes), and vaporized water are neglected in this study [1].

A single downhole log measurement of 37 °C at a depth of 1058 m bsl [7] exists to constrain the virgin rock temperature profile through the Utsira formation. This measurement is subject to an uncertainty of several °C [8]. However, accurate reservoir characterization of the Sleipner East field, from 21 drill stem tests, give a reservoir temperature of 101.7 ± 0.5 °C at 2600 m depth [8]. By accounting for the differences in thermal conductivity of the rocks above this depth, the temperature of the Utsira Formation at 1058 m bsl is expected to be 42.5 °C. Near the 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$^3$. Thus a slightly higher temperature could result in a much lower CO$_2$ density. Additionally, the CO$_2$ will be heated during compression from the wellhead conditions (25 °C, 64 bar) and down through the injection well. Because of the high injection rates, the injected CO$_2$ may experience close to adiabatic conditions, putting the temperature at a maximum of 57 °C at the bottom of the injection well. This could create an ultra-low density front or plume of CO$_2$ surrounded by cooler CO$_2$. Until recently, most of the work that has been done in reservoir simulations and in estimating the in situ CO$_2$ mass has assumed that the 37 °C measurement is correct, and that the CO$_2$ density is 650-700 kg/m$^3$. Therefore, determining the in situ CO$_2$ density is important for the long-term modeling and predictions.

**Gravity and pressure data acquisition and results**

As CO$_2$ is injected into the Utsira sand, it displaces the water from the pore space in the sand, causing an effective bulk density decrease within the formation. In this study, seafloor gravity measurements were made with an ROV carried instrument shown to be capable of measurement accuracies of 18 µGal or less [9-11], comparable to land surveys. The instrument used is the ROVDOG (Remotely Operated Vehicle deployable Deep Ocean Gravimeter), which contains three Scintrex relative gravity sensors [11]. Gravity measurements were made on top of concrete benchmarks, meant to serve as stable platforms to place the instruments in exact registration on the seafloor. The benchmark locations are shown in Figure 1. The first gravity survey was carried out from August 16-20, 2002. Each station was visited at least 3 times, to give adequate control on drift and survey accuracy. To aid with tide corrections, pressure was
continuously recorded over the duration of the survey using portable seafloor instruments located at the center of the survey area. A total of four CTD measurements were made at benchmark SP09. The 2005 gravity survey was carried out from September 2-6, with each station visited at least 2 times. Reference tide gauges were deployed at benchmarks SP20 and SP9, and 11 CTD measurements were made.

After correcting gravity values for tides (using the tide model SPOTL [12]), instrument temperature, tilt, and drift, the uncertainty is 4.3 \( \mu \text{Gal} \) in 2002 and 3.5 \( \mu \text{Gal} \) in 2005 (Figure 2a). The uncertainty in the relative depth estimates is 0.37 for 2002 and 0.54 cm for 2005. Figure 2b shows the residuals after the mean value of a station is subtracted from each measurement at that station. Details of the pressure (depth) processing can be found in Stenvold et al. [13].

Figure 1. Benchmark locations are shown by white circles. The rim of the seismically imaged CO\(_2\) bubble by 2001 is shown as a blue line. The inset shows the location of the Sleipner platform with respect to southern Norway. Also shown is a smoothed version of the gravity residuals after correcting for depth and a long wavelength trend. Note the spatially coherent gravity decrease from 2000 to 4000 m easting.

Figure 2. a) The scatter of repeated gravity measurements after the mean of each station has been subtracted from each measurement. Each point is the average of the three gravimeters. b) The scatter of repeat pressure measurements after the mean for each station has been subtracted. Each point is the average of the three pressure gauges. See the text for details.
**Time-lapse results**

Changes in gravity over time are found by subtracting the 2002 results from the 2005 results. A long-wavelength gravity trend increasing to the west can be seen, with a maximum value at benchmark SP01 of 30–40 µGal. The most likely source of this signal is from natural gas that is being produced from the Ty formation reservoir, which lies about 1.5 km below the Utsira formation and west of the injection point. Production from this reservoir is expected to cause an increase in local gravity due to a rise in the reservoir water as the natural gas is removed. A forward model was calculated based on Ty formation reservoir geometry, porosity, temperature, gas production data, and data from monitoring wells (all proprietary information), and matched to the gravity data.

The time-lapse gravity (after the Ty forward model has been removed) and depth data are shown together in Figure 3a. The depth changes have a scatter of ~7 cm, with no apparent spatial correlation. Changes in the gravity coincide nicely with the changes in depth, providing assurance that the observed depth changes are real. These depth changes are most likely due to subsidence from sediment scouring around each benchmark. Sediment scouring is common in this part of the North Sea, especially in shallow water such as the Sleipner area, indicating that the benchmarks are not as stable as we had hoped.

The theoretical vertical gravity gradient in the ocean is 0.220 mGal/m (the free water gradient). The time-lapse gravity data was inverted to solve for a scale factor to the Ty formation model and the gravity gradient simultaneously. Gravity data from only the outer benchmarks was used, to remove the influence of the injected CO₂ from the inversion. Figure 3b shows the best fitting line to the dg versus dz data after the Ty formation model has been subtracted. The result is \( \frac{dg}{dz} = 0.16 \pm 0.04 \) mGal/m. This value is significantly lower than the value of the expected gradient. A combination scouring and benchmark settling would decrease the gradient to between 0.182 and 0.155 mGal/m, depending on the amount of benchmark settling.

Figure 1 shows the resulting corrected time-lapse gravity values. Each point has been smoothed by averaging all observations within a 500 m radius of that point. The total time-lapse uncertainty in each gravity measurement is 5.3 µGal, and the uncertainty in each time-lapse depth change is 0.9 cm. A dip in the gravity with a maximum decrease of about 15 µGal can be seen in the data from an easting of ~2000 m to ~3000 m. This is the region of expected gravity decrease due to CO₂ injection. Benchmark SP3 (located at an easting of about 1000 m) also shows a dip in gravity. However, this is not spatially correlated with surrounding sites, suggesting that it is a spurious point. Benchmarks SP29 and SP30 are similarly low, suggesting spread of CO₂ to the south.

**3-D forward modeling**

The seismic data from 1999 and 2001 were used to build gravity forward models of injected CO₂ for two scenarios. The first is for an average CO₂ density within the reservoir of 700 kg/m³, and the second is for an average CO₂ density of 550 kg/m³. These correspond to low reservoir temperature (35 °C) and high reservoir temperature (45 °C) scenarios, respectively. These models contain supercritical CO₂ in two distinct parts. The first is CO₂ residing in thin, high saturation layers, which have ponded beneath thin inter-reservoir shale layers. The second is a low saturation diffuse volume occupying the space between the high saturation layers. The high-density model predicts a maximum change between 1999 and 2001 of about 2.7 µGal/year, while the low-density model predicts a maximum change of about 4.5 µGal/year. Additionally, reservoir flow models were built by SINTEF, an independent research organization, to model CO₂ migration and accumulation. The models incorporate features seen in the seismic data, and are used to predict CO₂ migration and accumulation from 2002 until 2005, when no seismic data is available. These models are post-processed to model the gravimetric response on the seafloor. Again, both low reservoir temperature and high reservoir temperature scenarios were generated. They produce a gravity decrease of 2.2 to 2.4 µGal/year for a CO₂ density of 700 kg/m³ and 4.7 µGal/year for a CO₂ density of 550 kg/m³, similar to the models based on seismic response from 1999 to 2001 [14].
Discussion and conclusion

For a given Utsira temperature, reservoir simulations predict gravity changes that are on the same order of magnitude as pre-2002 seismic models. This insensitivity to detailed flow geometry suggests that the magnitude of the maximum time-lapse gravity signal is due primarily to CO₂ density. Figure 4a shows a smoothed version of the forward model predictions and the observed gravity. The smoothing was done by averaging each point with its nearest neighbors to the east and west. Three points from about 2200 to 3200 m easting include the nearby points off the northwest-
southeast trending main line, so that all the time-lapse gravity information is collapsed onto a single line. The error bars for this plot were calculated as the time-lapse uncertainty (5.3 µGal) divided by the square root of the number of points included in the average. The difference in the shape of the reservoir models and seismic model reflects the differences between the CO₂ flow geometries. The flow in the idealized reservoir simulation models is simplified and has a much larger westward component than the seismic data indicate. The maximum difference between the high and low CO₂ density models is about 7 µGal, which is very close to the 5.3 µGal uncertainty in each measured value, however, by smoothing the data and models, observations fit the high temperature seismic model the best. Linear extrapolation of the smoothed seismic models to include a wide range of CO₂ density suggests that the CO₂ has an average density of about 530 kg/m³ (Figure 4b). 95% confidence intervals of average density are estimated to be ±65 kg/m³, from the χ² fit of the smoothed data, demonstrating the resolving power of this technique. However, this estimate does not include uncertainty in the models, including uncertainties in the seismic data, uncertainties in determining CO₂ saturation from seismic pushdown, and unknown flow geometry from 2002 to 2005. In another few years, as signal levels increase and new seismic data is acquired, more confidence can be placed on the density estimate.

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