Seismic monitoring of CO_2 injected into a marine acquifer

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SUMMARY

Since October 1996 Statoil has injected CO_2 into a saline aquifer for disposal. Monitoring the behaviour of the CO_2 in the sand formation and the sealing capacity of the overlying shale cap rock are key elements in understanding the dynamics of the injection process. A repeated 3D seismic dataset was therefore acquired in 1999, after injection of about 2 million metric tons of CO_2. The time-lapse data show a large increase in reflectivity and a large push-down of reflections caused by the injected CO_2. Gas at different levels within the sand are probably trapped by thin shale layers. Only a small part has reached the top of Utsira Fm., and no signs of CO_2 are observed above the top seal.

INTRODUCTION

The North Sea Sleipner West field contains hydrocarbon gas with up to 10 % CO_2. Instead of emitting this greenhouse gas into the atmosphere, Statoil and partners decided to re-inject the CO_2 into a saline acquifer (Utsira Fm.) at a depth of 800-1100 m below sea level (Figure 1). This will save about 20 million metric tons of CO_2 from being added to the atmosphere during the fields lifetime (Baklid et al. 1996). The Utsira Fm. consists of sandstones with 35-40 % porosity and 1-8 D permeability, and with some thin (<1m) shale layers in-between, and is sealed by thick shales. The formation extends over large parts of the North Sea.

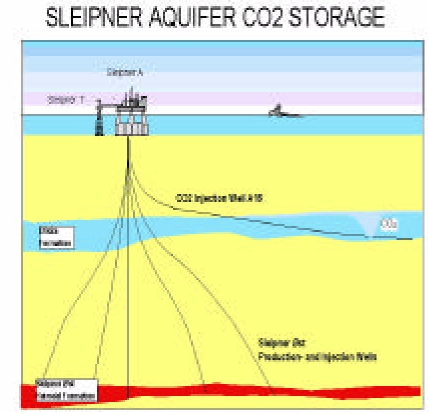

Figure 1: Cross-section through the injection well.

Injected CO_2 will have temperatures and pressures close to the critical point (35-40 °C and 80-110 bar, Baklid et al. 1996). A few percent methane is injected together with the CO_2. This causes significant uncertainties in density and solubility of injected CO_2. Numerical flow modelling suggest that most of the CO_2 will be in gas phase, and that there will be no major difference in areal distribution between free and dissolved CO_2. Variations in factors as density and permeability suggest that vertical permeability and horizontal shales mainly control the short-term CO_2 migration. In the presence of thin shales, CO_2 is expected to temporary accumulate in bubbles more than 10 m thick underneath. In the long term (> 25 years), migration is expected to be controlled mainly by the topography of the top seal and the horizontal permeability.

A multi-institutional research project SACS (Saline Aquifer CO_2 Storage) has been formed to monitor and predict the fate of the injected CO_2. The research institutions are focusing on storage capacity, cap seal capabilities and behaviour of CO_2 in the sand, as CO_2-water-rock interactions, pressure and phase properties, flow properties and acoustic properties. Two major challenges in the SACS project are the identification of methods for monitoring the dissemination of CO_2 and the sealing capacity of the cap rock.

SELECTION OF MONITORING TECHNIQUE

An observation well gives direct measurements, but drawbacks are high cost, no areal information and a risk that the CO_2-containing structure could be punctured. This led us to consider geophysical monitoring techniques. Recent time-lapse seismic success stories, using coventional streamer acquisition, stimulated Statoil and SACS partners to evaluate such options. A good-quality pre-injection 3-D seismic survey was shot in 1994, and new data can be compared against this base survey. With todays efficient multi-streamer seismic vessels sufficient coverage can be obtained in only two-three days of shooting. A "conventional" 4-D approach was therefore preferred as monitoring technique by the SACS project.

More exotic seismic techniques as borehole receivers (in the injection well) or passive listening were thought to be technically more uncertain and probably also more expensive.

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Non-seismic techniques, as repeated gravity or resistivity measurements are still being considered for future work - as complementary information.

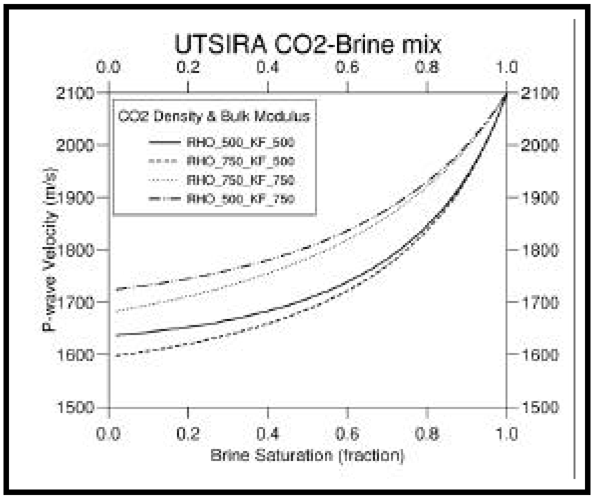

Figure 2 : Model of P-wave velocities for a homogenous mix of Utsira formation water (brine) and injected free CO_2 gas. A total of 4 different combinations of the two acoustic properties of CO_2 gas are shown (the curve RHO_750_KF_500 represent 0.75 g/cm^3 density and 0.5 GPa bulk modulus).

EXPECTED CHANGES IN SEISMIC RESPONSE

Prediction of changes in seismic response were based on acoustic rock properties estimated from well logs and assumed acoustic properties of CO_2 under relevant pressures and temperatures. We used a range of different values for density and bulk modulus to address the large uncertainties in CO_2 properties. CO_2 has a high compressibility, and because the rock matrix in the Utsira Sand is weak, the compressional velocity is also unusually sensitive to the compressibility of the fluid. Therefore, the presence of gas induces a dramatic drop of the compressional wave velocity even for moderate gas saturations. A model with a homogenous distribution of free CO_2 gas at different saturations influences the P-wave velocity within the Utsira formation as shown in Figure 2. Figure 3 demonstrates the large impact a thick column of trapped CO_2 gas is expected to have on the Top Utsira Fm. reflection coefficient. A volumetric free CO_2 gas content of 25% (and 75% formation water), will double the reflected amplitude, while fully substituting the formation water by free CO_2 gas is expected to "brighten" the amplitude by a factor of 3. We do not expect to see any large AVO effect (i.e. variation with incidence angle) at any gas/water mixes. The large contrasts in seismic properties could cause even thin layers containing CO_2 (e.g. trapped underneath shales) to be detected in a time-lapse survey.

Travel time delays up to 25 ms ("push-down") are predicted in a 100 m thick fully CO_2 saturated Utsira formation. A heterogeneous volumetric 50/50 mix, of scale smaller than the wavelength, will result in a maximum of 50% reduction of this delay. The travel time-saturation relation will for such mixes be more linear than the homogenous velocity-saturation relation seen in Figure 2.

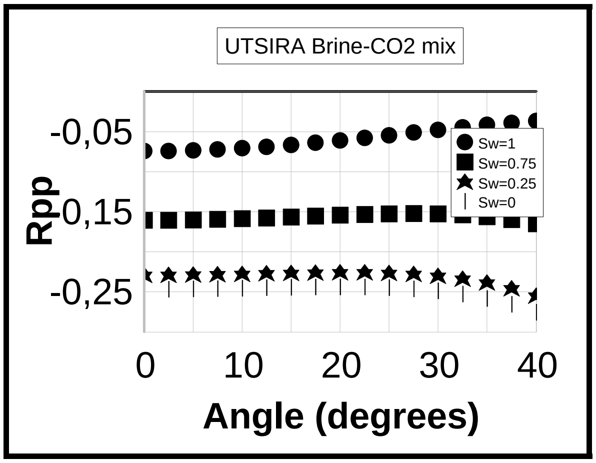

Figure 3 : Expected AVO properties at Top Utsira Fm. for different water saturations. The reflection coefficient (R_{pp}) is shown as a function of incidence angle, for the selected CO_2 properties of 0.5 GPa bulk modulus and 0.5 g/cm^3 density.

SEISMIC DATA ACQUISITION AND PROCESSING

The monitor survey was acquired in October 1999, after about 2 million tons CO_2 was injected during three years. The baseline survey from 1994 was shot primarily for imaging the much deeper hydrocarbon gas reservoir. Towing depths of 6 m and 8 m gives a useable frequency band up to about 70 Hz. Vital parameters, as shooting direction, nominal line spacing and tow depths were kept identical to the base survey (Table). Only the shotpoint interval was changed, from 18.75 m to 12.5 m, to get higher fold. This was made possible by a shorter recording time in 1999. A potential for increasing vertical resolution by shallower towing depths was acknowledged, but this would introduce another change from the base survey, make the data more susceptible to ocean wave noise and in this case also require some added mobilisation time.

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In the following simultaneous processing/reprocessing of the vintages, care was taken to equalize the wavelets, timing and gain of the surveys, which is important for a high-quality result. The further processing flow was kept identical, except for stacking and migration velocities applied in the CO_2 region.

The resulting time-lapse data are well repeatable and of good image quality. Because the CO_2 gas causes large changes in seismic response, we believe we would still observe the main outline of the CO_2 bubble with a less careful repeat of acquisition and processing parameters. However, a higher degree of repeatability makes quantitative use of the data more reliable.

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Shooting direction	N-S	N-S
Shotpoint interval (flip-flop)	18.75 m	12.5 m
No. of airguns	30	24
Total airgun volume	3400 in^3	3542 in^3
No.of streamers	5	4
Crossline nominal spacing	25 m	25 m
Source towing depth	6 m	6 m
Streamer towing depth	8 m	8 m
Residual swath-consistent time shifts		yes
Residual global spectral matching		yes
Stack fold normalization	sqrt(40)	sqrt(60)

Table: Main acquisition and processing parameters.

TIME-LAPSE OBSERVATIONS AND INTERPRETATIONS

The 1999-data show a large increase in reflectivity within the Utsira Fm. compared to the 1994-vintage (Figure 4). This is further enhanced in the difference data, where the "static" geology is removed from the image. Strong reflections arise from several (mainly four) vertical levels, of which top Utsira Fm. is the shallowest. Difference amplitudes are up to three times as large as the initial reflections from this area. Most of the new events show ~zero-phase wavelets, as if they originate from single acoustic boundaries. Reflectivity changes are more extensive at the lower levels, suggesting that most of the CO_2 has not migrated up to the top of the sand yet. These results indicate the presence of a heterogeneous saturation pattern, and therefore the presence of CO_2 gas flow barriers, likely to be thin shale layers. By adjusting the vertical spacing and lateral size of the shale layers in the numerical model, a good match between the seismic images and the model output was achieved.

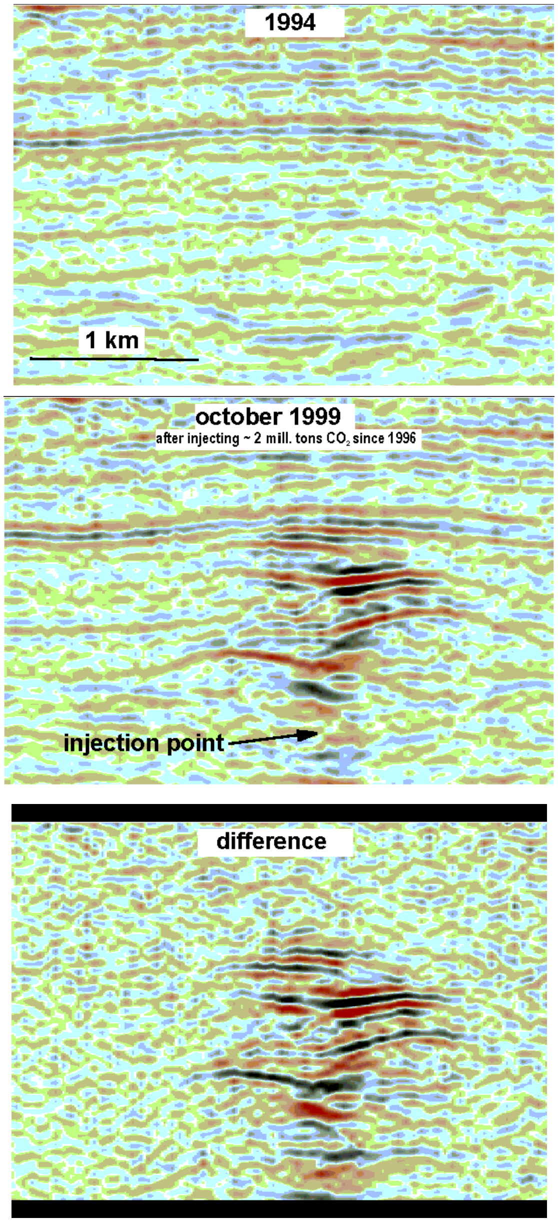

Figure 4: Seismic section through the injection point, in 1994 (above), 1999 (middle) and difference (below).

In map view the reflectivity changes are restricted to a semicircular area around the injection point with radius less than 1 km (Figure 5). The largest portion of the anomaly is north and east of the injection point, and it has a slightly elongated shape in the N-S direction.

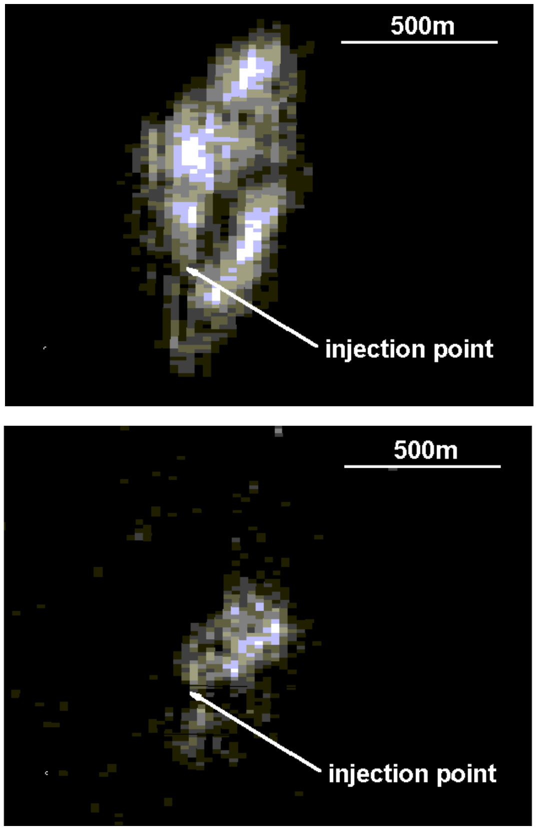

Figure 5: Amplitude attribute maps 150 ms below top Utsira Fm. (above) and at the top Utsira Fm. (below).

A distinguished velocity push-down can be observed for all reflections beneath top Utsira Fm. The event 60 ms below the top has a push-down of 10 ms, and this increases further down to about 20 ms for events beneath the entire CO_2-cloud. The area of largest push-down is less than the area of reflectivity change, only 200-400 m wide, suggesting the CO_2 concentrations are decreasing sideways towards the saturation front.

The areal extension of CO_2 deviates slightly from the contour lines of topographic maps near top Utsira Fm. and could suggest the flow is not completely controlled by gravity. However, the uncertainties in depth conversions are significant in this flat area.

The non-linear velocity-saturation relation complicates quantitative estimates of saturations. Further, reflectivity observations may well pick up sharp saturation contrasts, as the front of the CO_2 cloud, but give less information on the average saturation content within larger rock volumes. The velocity push-down is an accumulated effect of all CO_2 saturations above, and is perhaps more easy to relate to volumes of free CO_2 gas. The seismic observations and derived volumetric distribution seem to be within the range of predictions given by dynamic models.

CONCLUSIONS

A unique CO_2 injection into a marine acquifer has been succesfully monitored with repeated surface seismic measurements. The data reveal the extent and internal shape of the "CO_2-bubble", and the method is an important tool in learning about the fate of disposed CO_2.

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