Abstract

Since September 1996, Statoil and its Sleipner Partners have injected CO₂ into a saline aquifer at a depth of approximately 900 m, with an injection rate of up to 1 million tons per year. The aquifer, comprising the Utsira Sand, has a thickness of more than 200 m near the injection site and is sealed by thick shales. A multi-institutional research project SACS (Saline Aquifer CO₂ Storage) was formed to predict and monitor the migration of the injected CO₂. 3-D seismic data were acquired over the area in 1994, prior to injection and again in 1999 after 2MT of CO₂ had been injected. At several levels within the Utsira Sand, a large increase in reflectivity has been observed on the time-lapse seismic data. Those changes are restricted to an elliptical area of less than 1 km radius, markedly elongated in the NNE-SSW direction. Below the CO₂ bubble a pushdown is evident on the time-lapse seismic data. This is caused by lower acoustic velocities in CO₂ saturated rock with respect to water saturated rock. Gassmann modeling combined with the observed time delays gives an estimate of the total volume of CO₂ in place. With the density of the CO₂ known under reservoir conditions (P-T analysis) the total mass of injected CO₂ can be determined. A sensitivity analysis with respect to the input parameters has been performed and the mass calculations have been compared to the actual injected mass.

Introduction

Time-lapse seismic surveying has proved to be a suitable geophysical technique for monitoring CO₂ injection into a saline aquifer. The effects of the CO₂ on the seismic data are large (Eiken et al, 2000), both in terms of reflection amplitudes and also in the time delays observed (velocity pushdown effect). In the Utsira Sand with P-T conditions above the critical point the CO₂ has a high compressibility. Because the rock matrix in the (poorly-cemented) Utsira Sand is weak, the compressional velocity is very sensitive to the compressibility of the fluid. Therefore, the presence of CO₂ induces a pronounced drop in the compressional wave velocity even for moderate gas saturations, leading to a clear change in seismic response. This is expressed in a change in reflection amplitudes and in a change in traveltime through the CO₂ accumulations (“velocity pushdown effect”). In this study the latter is used to estimate the total volume and mass of CO₂ in place under reservoir conditions. This result is compared to the amount of actually injected CO₂.
Estimation method of the CO₂ volume from seismic data

To estimate the total volume of the CO₂ bubble in the reservoir using the pushdown effect the following simplified equation has been used:

\[
Vol_{CO₂} = \Phi \times dx \times dy \int_z \frac{V_{SW=1} \times V_{(1-S_w)}}{2 \times (V_{SW=1} - V_{(1-S_w)})} \times (1-S_w) \times (TWT_{99} - TWT_{94}) \, dz
\]

Gassman factor

With:

- \( Vol_{CO₂} \) is the volume of CO₂ under reservoir conditions (Rm³)
- \( V_{SW=1} \) is velocity in water saturated sandstone (‘94) (m/ms)
- \( V_{(1-S_w)} \) is velocity in CO₂ saturated sandstone (‘99) (m/ms)
- \( S_w \) is water-saturation and \((1-S_w)\) is CO₂-saturation
- \( \Phi \) is porosity
- \( dx, dy \) are the inline and crossline spacing (product is the bin-size) (m)
- \( TWT_{99} \) is an interpreted traveltime picked below the CO₂ after injection (‘99) (ms)
- \( TWT_{94} \) is the same interpreted traveltime before injection (‘94) (ms)

This method assumes porosity, saturation and velocities within both the water and CO₂ saturated rock known. The sensitivity to variations especially in these parameters has been investigated. The Utsira Sand is considered to be a homogenous, unconsolidated sand with a uniformly high porosity of 35-37%. For computational reasons one single saturation height function has been assumed for the entire reservoir interval. Note however that this function has been applied for each individual accumulation within the reservoir. The elastic velocities for the water and CO₂ saturated rock are based on well log analysis combined with Gassmann modeling.

Gassmann modeling

The input parameters for the Gassmann modeling have been determined from well log analysis, including an estimation of the shear wave velocity in water saturated sandstone. The largest uncertainty appears to be on the bulk modulus of the CO₂ under reservoir conditions (P-T). Figure 1 shows the modeling results for the velocities as a function of water (-CO₂) saturation for three different bulk moduli. Laboratory experiments demonstrate, that the bulk modulus K is most likely \(< 0.675 \text{ GPa}\). This implies generally a fairly constant P-wave velocity \(< 1450 \text{ ms}^{-1}\) for the Utsira sand for CO₂ saturations in the range of 20 – 100 \%.
Push-down effect observed in the seismic data

The pushdown effect on the seismic data has been determined by cross-correlating the seismic signals below the CO₂ bubble of the 1994 seismic survey (before injection) with the 1999 seismic survey (after 3 years of injection) on a trace-by-trace basis. From this cross-correlation a time-lag due to velocity pushdown can be estimated robustly and mapped accurately (Figure 2). The maximum push-down in TWT amounts to 37 ms corresponding to a local CO₂ saturated rock column of about 93 m under the assumptions mentioned earlier.

In places the cross-correlation provided very poor results because the seismic data quality below the CO₂ was insufficient. At these locations ‘holes’ in the time-lag map have been filled in by manual interpretation.

Figure 1: Result of the Gassmann modeling for three different bulk moduli of the CO₂.

Figure 2: Time-lag in ms resulting from the cross-correlation between the seismic signals below the CO₂ bubble of the 1994 survey (before injection) and of the 1999 survey (after three years of injection).
Results

The results of the mass calculation derived from seismic data of the CO₂ bubble after three years of injection are summarized in Table 1. Based on the P-T reservoir conditions a density of the supercritical CO₂ of 600-650 kg/m³ is assumed. The truly injected mass amounts 2.28 Mtonnes of CO₂.

Table 1: Results of the CO₂ mass calculation from the seismic data under reservoir conditions compared to a truly injected mass of 2.28 Mtonnes of CO₂.

<table>
<thead>
<tr>
<th>Density of the CO₂ (kg/m³)</th>
<th>Velocity in Utsira Sand with CO₂ (m/s)</th>
<th>Porosity of the Utsira Sand (%)</th>
<th>Calculated mass of CO₂ (Mtonnes)</th>
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</table>

Conclusions

In this study the mass of injected CO₂ under reservoir conditions has been estimated from seismic data and compared to the actual injected quantity. Such an estimation is important to verify whether all injected CO₂ is within our area of interest and to narrow down uncertainties on a number of reservoir parameters. In general the estimates tend to be too large favoring lower velocities in the CO₂ saturated sand. Refinement of the models reducing the uncertainty margins is in progress. The analysis will be extended with a new 2001 TL-seismic dataset.

Acknowledgements

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References