H-16 ESTIMATION OF THE MASS OF INJECTED CO_2 AT SLEIPNER USING TIME-LAPSE SEISMIC DATA

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Abstract

Since September 1996, Statoil and its Sleipner Partners have injected CO_2 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 CO_2 Storage) was formed to predict and monitor the migration of the injected CO_2. 3-D seismic data were acquired over the area in 1994, prior to injection and again in 1999 after 2MT of CO_2 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 CO_2 bubble a pushdown is evident on the time-lapse seismic data. This is caused by lower acoustic velocities in CO_2 saturated rock with respect to water saturated rock. Gassmann modeling combined with the observed time delays gives an estimate of the total volume of CO_2 in place. With the density of the CO_2 known under reservoir conditions (P-T analysis) the total mass of injected CO_2 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 CO_2 injection into a saline aquifer. The effects of the CO_2 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 CO_2 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 CO_2 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 CO_2 accumulations ("velocity pushdown effect"). In this study the latter is used to estimate the total volume and mass of CO_2 in place under reservoir conditions. This result is compared to the amount of actually injected CO_2.

Estimation method of the CO_2 volume from seismic data

To estimate the total volume of the CO_2 bubble in the reservoir using the pushdown effect the following simplified equation has been used:

$$Vol_{CO_2} = \Phi * dx * dy * \int_z \frac{V_{S_w=1} * V_{(1-S_w)}}{2*(V_{S_w=1} - V_{(1-S_w)})} * (1-S_w) * (TWT_{99} - TWT_{94}) \; dz$$

Gassman factor

With:

Vol_{CO_2}	is the volume of CO_2 under reservoir conditions (Rm^3)
$V_{S_w=1}$	is velocity in water saturated sandstone ('94) (m/ms)
$V_{(1-S_w)}$	is velocity in CO_2 saturated sandstone ('99) (m/ms)
S_w	is water-saturation and $(1-S_w)$ is CO_2-saturation
Φ	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 CO_2 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 CO_2 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 CO_2 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 CO_2 under reservoir conditions (P-T). Figure 1 shows the modeling results for the velocities as a function of water ($-CO_2$) saturation for three different bulk moduli. Laboratory experiments demonstrate, that the bulk modulus K is most likely << 0.675 GPa. This implies generally a fairly constant P-wave velocity < 1450 ms^{-1} for the Utsira sand for CO_2 saturations in the range of 20 – 100 %.

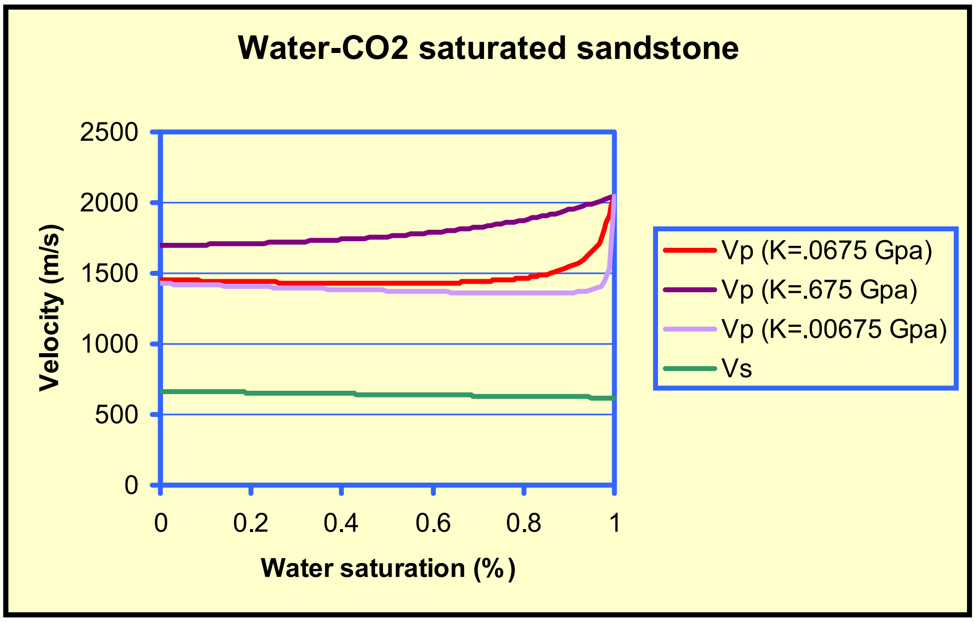
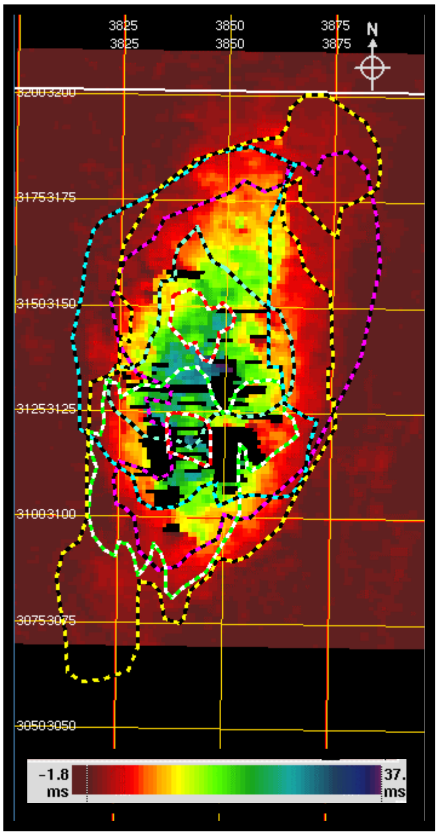


Figure 1: Result of the Gassmann modeling for three different bulk moduli of the CO_2.

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 CO_2 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 CO_2 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 CO_2 was insufficient. At these locations 'holes' in the time-lag map have been filled in by manual interpretation.

Figure 2: Time-lag in ms resulting from the cross-correlation between the seismic signals below the CO_2 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 CO_2 bubble after three years of injection are summarized in Table 1. Based on the P-T reservoir conditions a density of the supercritical CO_2 of 600-650 kg/m^3 is assumed. The truly injected mass amounts 2.28 Mtonnes of CO_2.

Table 1: Results of the CO_2 mass calculation from the seismic data under reservoir conditions compared to a truly injected mass of 2.28 Mtonnes of CO_2.

Density of the CO2 (kg/m3)	Velocity in Utsira Sand with CO2 (m/s)	Porosity of the Utsira Sand (%)	Calculated mass of CO2 (MTonnes)
600	1279	0.35	2.14
600	1332	0.35	2.44
600	1378	0.35	2.74
600	1454	0.35	3.35
600	1596	0.35	5.05
650	1279	0.35	2.31
650	1332	0.35	2.64
650	1378	0.35	2.97
650	1454	0.35	3.63
600	1279	0.37	2.26
600	1332	0.37	2.58
600	1378	0.37	2.90
600	1454	0.37	3.55

Conclusions

In this study the mass of injected CO_2 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 CO_2 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 CO_2 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.

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