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PRELIMINARY REPORT

TITLE

Evaluations of to what extent CO_2 accumulations in the Utsira formations are possible to quantify by seismic by August 1999.

(Preliminary results for internal Statoil use only. More comprehensive results will be available as results from task 2.3, 2.4 and 5.3 in the SACS project).

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SUMMARY AND CONCLUSION

A simulation of the CO_2 injection history corresponding to the injection in Utsira formation from September 1996 to 15. August 1999 has been performed. A homogeneous and a heterogeneous reservoir model were tested based on the shallow anticline structural trap near the injection point. In both cases significantly accumulations of CO_2 with up to 20 m thickness will be present either under the cap rock or under the impermeable shales deeper in the formation. In the homogeneous case CO_2 will start to accumulate under the cap rock three weeks after the injection started. The CO_2 bubble will then gradually increase in radius until it reaches the spill point 1. December 1998 at 800 m radius. The CO_2 will then start to migrate to one of the three traps north, west or south of the injection trap. In the heterogeneous model the accumulation under the cap rock will be delayed with 34 months. However, large accumulations with a thickness up to 12 m will be present deeper in the reservoir.

An analysis of the change in seismic reflection coefficients when CO_2 replaces water has been performed. The combined results from reservoir simulation and seismic analysis suggest that the reflection from the CO_2 accumulation in the difference data may be as strong as the reflection from top Utsira in the base survey for a bubble CO_2 thickness, $\Delta z_{0,}$ as small as about 1 m. The presence of a thicker CO_2 accumulation is also detectable from reflections at reflectors located below the CO_2. Even if the value of Δz_0 is sensitive to uncertainties in the model parameters and to the repeatability of the survey, it indicates that the detection of CO_2 accumulations by use of time-lapse seismic data is feasible.

KEYWORDS ENGLISH	KEYWORDS NORWEGIAN
CO_2 injection	CO_2-injeksjon
Aquifers	Akviferer
Reservoir simulation	Reservoarsimulering
Seismic monitoring	Seismisk monitorering
Gassmann equation	Gassmann-ligningen

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1. Background

CO_2 has been injected into the Utsira formation since September 1996. In the SACS project (Saline Aquifer CO_2 Storage) the basic objective is to monitor the migration of CO_2 in order to be able to determine the fate of CO_2 both on short time scale (< 50 years) and on a long time scale (1000's of years).

2. Objective

The goal of this study is to estimate the influence of possible CO_2 accumulations in the Utsira formation by 15. August 1999 on seismic measurements as a background for the evaluation of the feasibility for a seismic survey during the summer 1999.

3. Reservoir simulation

Previous simulation of CO_2 injection into aquifers (Korbøll and Kaddour 1995, Lindeberg 1997) has shown that CO_2 readily will migrate to the sealing cap due to gravitational forces. A specific simulation on how fast this accumulation will occur is the objective for this part of the study.

3.1 Selection of reservoir segment in Utsira and basic data and assumptions.

From the supplied map of the Utsira top (Figure 3.1), a shallow anticline trap can be identified above the injection point. A simplified reservoir model has been built on the basis of a cylinder with 1600 m diameter below the circle shown on the figure. The actual model consists only of a 60° sector of this cylinder assuming an idealised radial geometry. In all cases the cap rock dip and extension from centre to spill point is kept constant (12.5 m dip on an 800 m radius). The real injection point is actually 300 m off the centre of the anticline, but for this simplified approach it has been placed in the centre at 960 m depth below sea mean level (add 78 m to achieve the true vertical depth relative to the rotary table on the Sleipner A platform). Initial hydrostatic pressure is applied and this pressure is maintained at the bottom of the periphery of the model corresponding to a situation with infinite extension of the whole formation. The injection well is horizontal and the perforation is 40 m of which only 20 will reach into the 60° sector, which is studied. The simulation is carried out with Eclipse 100 reservoir according to the method, fluid and relative permeability data used by Lindeberg (1996). The permeability is, however, somewhat higher according to recent measurements on Utsira cores carried out in the laboratories of SINTEF Petroleum Research. These preliminary results indicates that both the horizontal and vertical permeability is approximately 3 Darcy ($\sim 3 \cdot 10^{-12}$ m^2). The numerical grid consists of up to 10 000 radial grid blocks in the simulations presented here while up to 56 000 grid blocks was used in other simulations to study special problems. Molecular diffusion was not included during this simulation, while capillary pressure and solubility of CO_2 in brine were included.

There are uncertainties related to the fluid data due to the proximity to the critical point of CO_2. The reservoir conditions vary between 29 and 37°C and 80 and 96 bar while the critical point for CO_2 is 31°C and 74 bar. Not only can small variations in pressure and temperature give dramatic variations in density, but also small amounts of methane contamination can result in large reductions in density. This uncertainty will apply both for the reservoir simulations and for the calculation of bulk modulus, which is important for seismic simulation. (The compressibility goes towards infinity at the critical point while the ratio C_p/C_v has a strong anomaly near the critical point.).

There exists experimental thermodynamic data for the CO_2/methane system in this range, but comprehensive computational work needed to take advantage of these data has not yet been completed. In these simulations the CO_2 data correspond to pure CO_2.

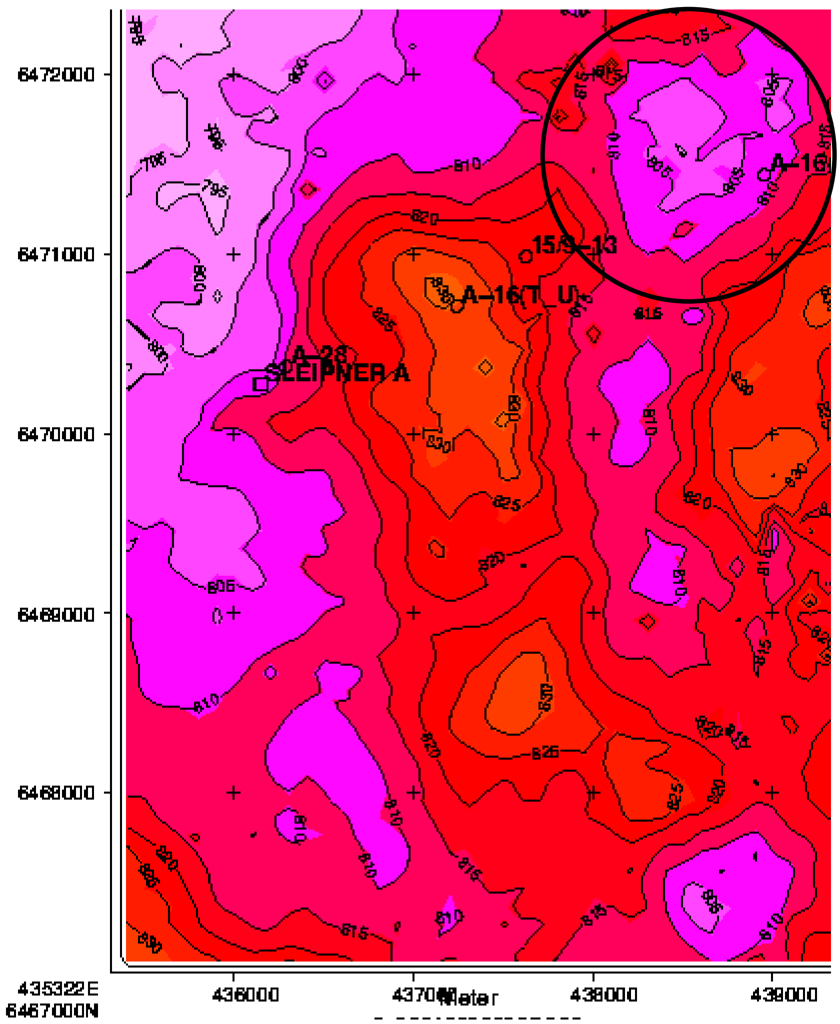

Figure 3.1 A map of the Utsira cap with the selected segment used in simulations indicated with a circle. The circle diameter is 1600 m.

3.2 Simulations on a homogeneous reservoir model

In this case it assumed that the reservoir is both a homogenous and isotropic body with a permeability of approximately 3 Darcy (the average from three laboratory measurements). The CO_2 migrates from the injection point to the cap seal in approximately three weeks. The CO_2 bubble will then gradually increase in radius until it reaches the spill point at 1. December 1998 at 800 m radius. The CO_2 will then start to migrate to one of the three traps north, west or south of the injection trap (Only the west and south trap is shown on the map cut out illustrated in Figure 3.1. The maximum thickness of the CO_2 gas cap at 15. August 1999 is 20 m (Figure 3.2). 12.5 m of this is due to the topography of the seal, while 7.5 m is a down-dip cone in the proximity to where CO_2 ascending from the injection well reaches the gas cap.

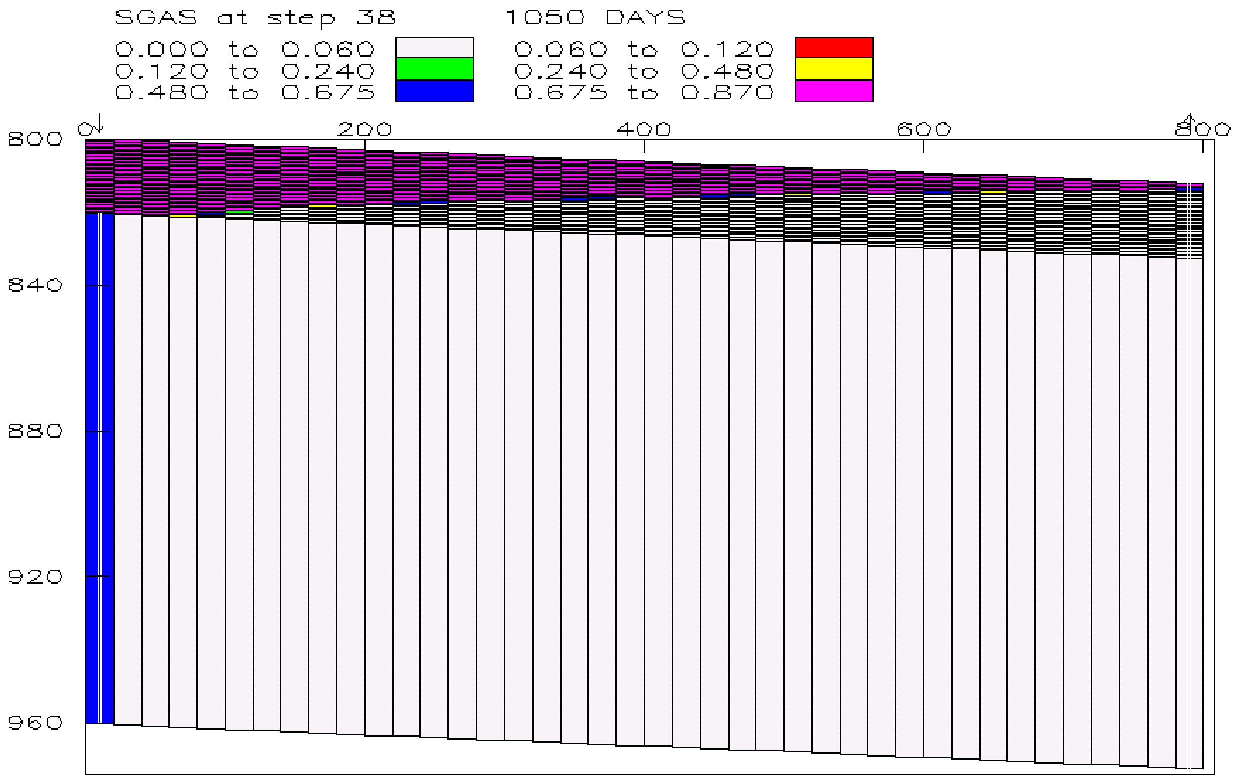

Figure 3.2 A vertical CO_2 saturation profile of the homogeneous reservoir model after 35 months of injection corresponding to the 15. August 1999. The CO_2 is injected in the lower left corner of the grid. Dimensions are in meters. The CO_2 has accumulated as a bubble in the anticline under the cap rock. The gas cap has not grown significantly since 1. December 1998 when the spill point was reached.

3.3 Heterogeneous reservoir model

In the heterogeneous reservoir model totally 5 impermeably layers of 400 m lateral extension have been distributed around the injection point corresponding to thin shale layers in a grid consisting of 10 000 blocks (250 x 40). This is illustrated in transmissibility plot in Figure 3.3. The impermeable layers are visible as dark lines in the figure. The impermeable layers are supposed to resemble possible heterogeneities seen on well logs from the Utsira formation in the Sleipner area. The transport properties of these shales are not known, but they are assumed to perfectly impermeable in this model in order to introduce an extreme perturbation in flow the pattern of ascending CO_2.

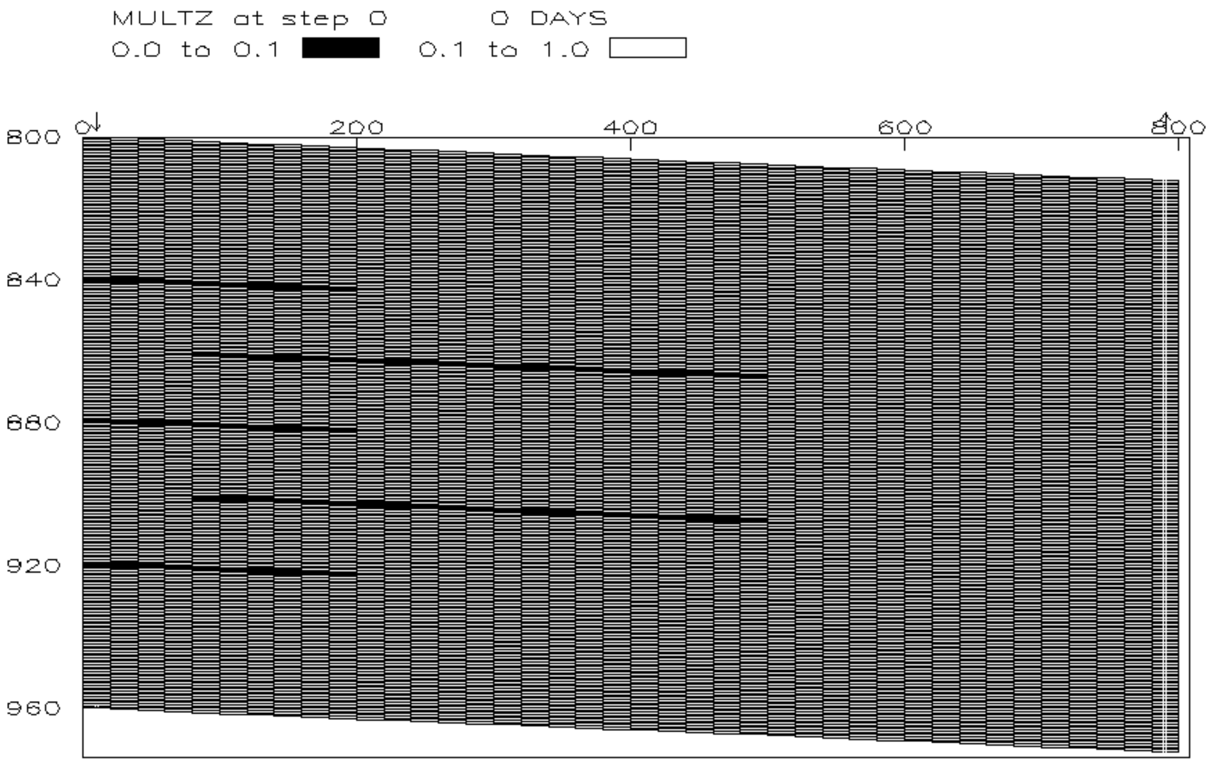

Figure 3.3 Transmissibility profile of the heterogeneous reservoir model. Illustration of the three anticline and two monocline impermeable layers introduced in the heterogeneous model. Only half of the central layers are seen in this reservoir cut-out due to symmetry.

The saturation profile after 35 months of injection is illustrated in Figure 3.4. Although the CO_2 has just recently reached the cap seal, there are large accumulations of CO_2 under the deeper impermeable layers. These bubbles has a thickness of up to 12 m and should also be detectable by seismic.

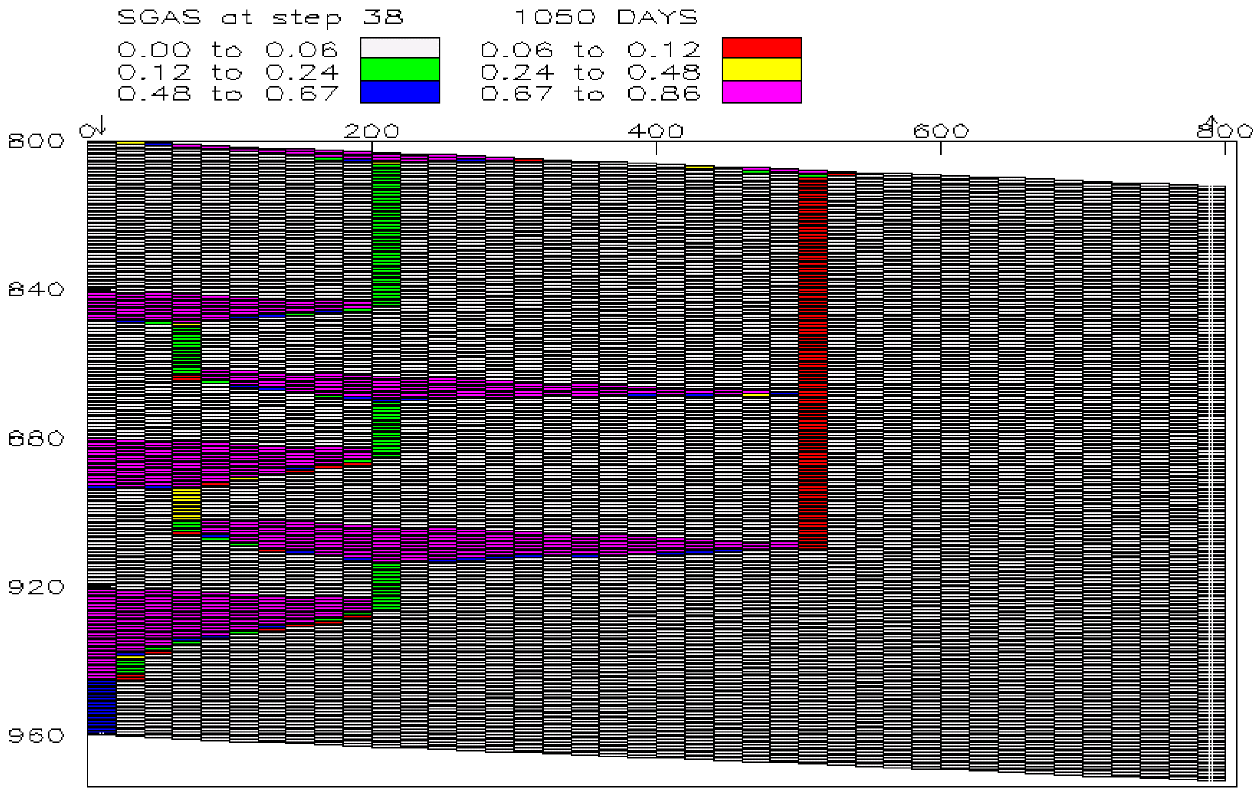

Figure 3.4 *Saturation profile of the heterogeneous reservoir model at 15. August 1999. The CO_2 has recently reached the cap seal but large CO_2 bubbles have accumulated under impermeable shales.*

3.4 Discussion of reservoir simulations

The large uncertainties in these simulations must be emphasised, especially due to the lack of information of transport properties in the entire vertical column. The two models were chosen to represent two extremes with respect to CO_2 migration. Other extreme heterogeneities could, however, be envisaged that will result in smaller CO2 accumulations. One such case is that there exists a deep semi-permeable shale that will trap large amount of CO_2, but at the same time allow CO_2 to migrate through the whole shale area. Large water volumes will in this case be contacted by CO_2 resulting in much larger fraction of CO_2 dissolved as shown by Lindeberg (1996). In the cases simulated above, only 5 to 12% of the injected CO_2 will be dissolved 1. December 1998.

4. Seismic evaluation

4.1 Introduction

The replacement of water by carbon dioxide as pore fluid introduces a change of the seismic parameters (density, and compressional and shear velocity). The replacement of water by carbon dioxide as pore fluid introduces a change of the seismic parameters (density, and compressional- and shear-wave velocities). This modifies the reflection coefficient at the top and base of the CO_2 accumulation and the travel-time down to reflectors located below the CO_2. The resulting changes of the seismic response can be visualised by taking the difference between seismic data acquired after and before the pore fluid change occurred. This should allow monitoring of CO_2 storage in the ground.

4.2 Theory and results

A simple model originally consisting of three homogeneous water saturated plane horizontal layers was considered. An additional layer of thickness z was introduced between the two reflectors, where the seismic parameters for the water-filled sediments are simply replaced by seismic parameters for CO_2-filled sediments by using the Gassmann equation. This layer can be located just below the top reflector representing the cap rock. It may also be located further down in case if the CO_2 seal is created by a very thin continuous shale layer that is not detectable on the seismic data. These two situations are represented in Figure 4.1 for the case of Sleipner, where the CO_2 is injected in the Utsira formation.

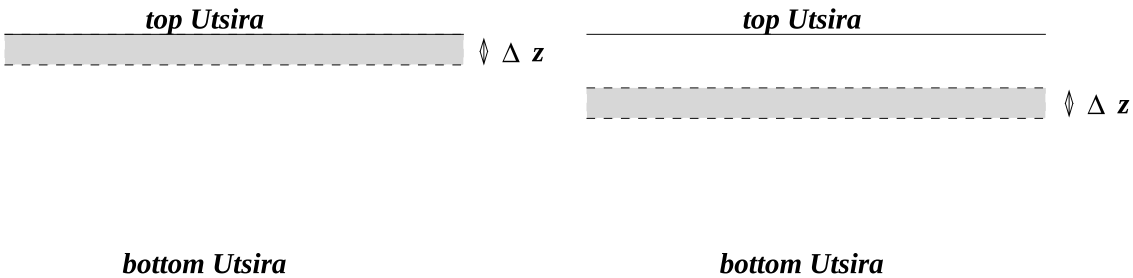

Figure 4.1: Simple geological model. The CO_2 accumulation (in grey) is located either just below the top Utsira reflector (left) or inside the Utsira formation (right).

In the situation where the CO_2 layer is located inside the Utsira formation (Figure 4.1 on the right), the presence of CO_2 introduces small negative and positive impedance contrasts at the top and base of the CO_2 layer respectively. Assuming small contrasts and a sharp transition between water and CO_2, there is a negative reflection coefficient R at the top of the CO_2 and a positive reflection coefficient - R at the base of the CO_2.

The main change in the seismic response caused by the presence of CO_2 consists of the superposition of the signals from these two reflectors. The arrival from the base of the

CO_2 comes with a small delay   t after the arrival from the top of the CO_2. For small time delays, we have

$$\delta RS(t) - \delta RS(t - \quad t) \quad R \quad t \frac{S(t)}{t}.$$

Hence the amplitude of the change in the seismic response is approximately proportional to the delay, and therefore to the thickness of the CO_2, and the signature in the difference data (the difference between the data acquired in the time lapse and base surveys) is equal to the derivative of the original pulse signature. The amplitude of the reflection at the CO_2 in the difference data reaches a maximum for a time delay   t about half the dominant period of the signal S(t). This corresponds to a CO_2 thickness about a quarter of the dominant wavelength for normal incidence. For larger CO_2 thicknesses, the signals from the base and top of the CO_2 accumulation separate (and the amplitude in the difference data does not increase any longer with increasing thickness). Since there is a linear relation between the contrasts in seismic parameters and the reflectivity when these contrasts are small, the presence of CO_2 has a similar effect in the other situation where the CO_2 is stored just below the top Utsira.

The presence of CO_2 affects also reflections from reflectors below the CO_2, e.g. the base Utsira, because of a decrease in the average velocity down to these reflectors. The resulting time delay is much smaller than   t. Hence, the response from these reflectors in the seismic difference data increases also linearly with the CO_2 thickness,   z (for small thicknesses), but reaches a maximum amplitude for much thicker accumulations (about a quarter of the wavelength divided by the relative change in compressional velocity).

To estimate the chance to succeed in monitoring CO_2 storage with seismic data at Sleipner, it is important to compare the amplitude of the signals in the difference data with the amplitude of the reflections at the top and base of Utsira in the base or time-lapse survey. Knowing the seismic parameters in the different layers, the thickness of CO_2 and the angle of incidence, the maximum amplitude of the signals corresponding to reflections at the CO_2 and at the base Utsira reflector in the difference data may be calculated. A source signature with unit amplitude is chosen, giving the results the dimension of a reflection coefficient.

In the tests, the source wavelet has a main frequency about 30 Hz (Figure 4.2). The parameters of the model are given in Table 4.1. The influence of fluid changes on the seismic parameters in Utsira is derived from the Gassmann equation and an averaging equation for density. In this test, the gas was pure CO_2 at a temperature of 33°C and a pressure of 92 bar. In these conditions, the bulk modulus of CO_2 is very low (about 0.07 GPa), and the replacement of the water by CO_2 creates a considerable drop of the compressional velocity. The contrast in seismic parameters at top Utsira is obtained from log information. For simplicity, it is assumed that the top and bottom Utsira have the same angle-dependent reflectivity. The pseudo reflectivities at the CO_2 and base Utsira in the difference data are compared to the original reflectivity at top Utsira in Figures 4.3 and 4.4 for different angles of incidence and different layer thicknesses.

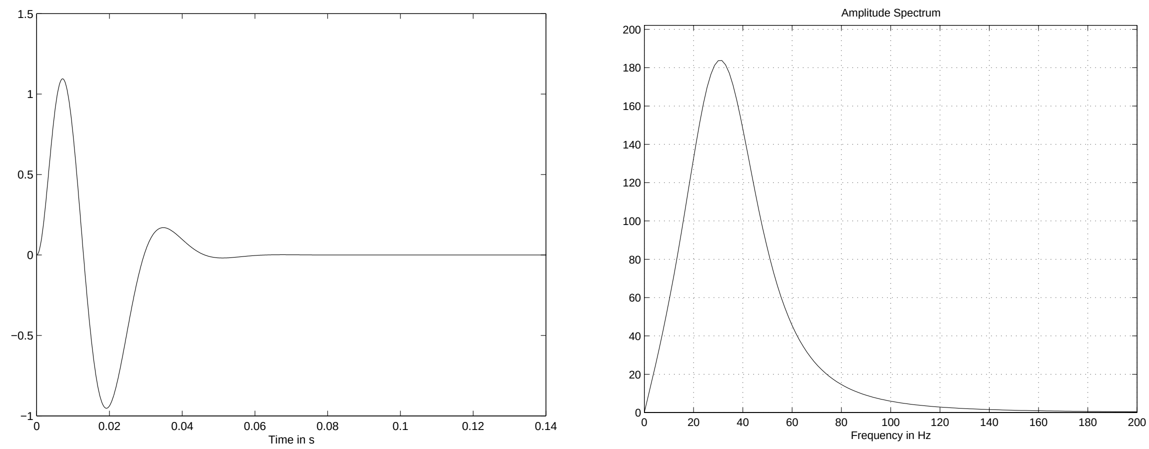

Figure 2: Source signature (left) and its frequency spectrum (right).

Table 4. 1: Model parameters for our test

Formation	**Velocity of p-waves, V_P (m/s)**	**Velocity of s-waves, V_S (m/s)**	**ρ (g/cm^3)**
Sediment above Utsira	2200	640	2.1
Water-saturated Utsira	2000	630	2.1
CO_2-saturated Utsira	1240	650	2.0

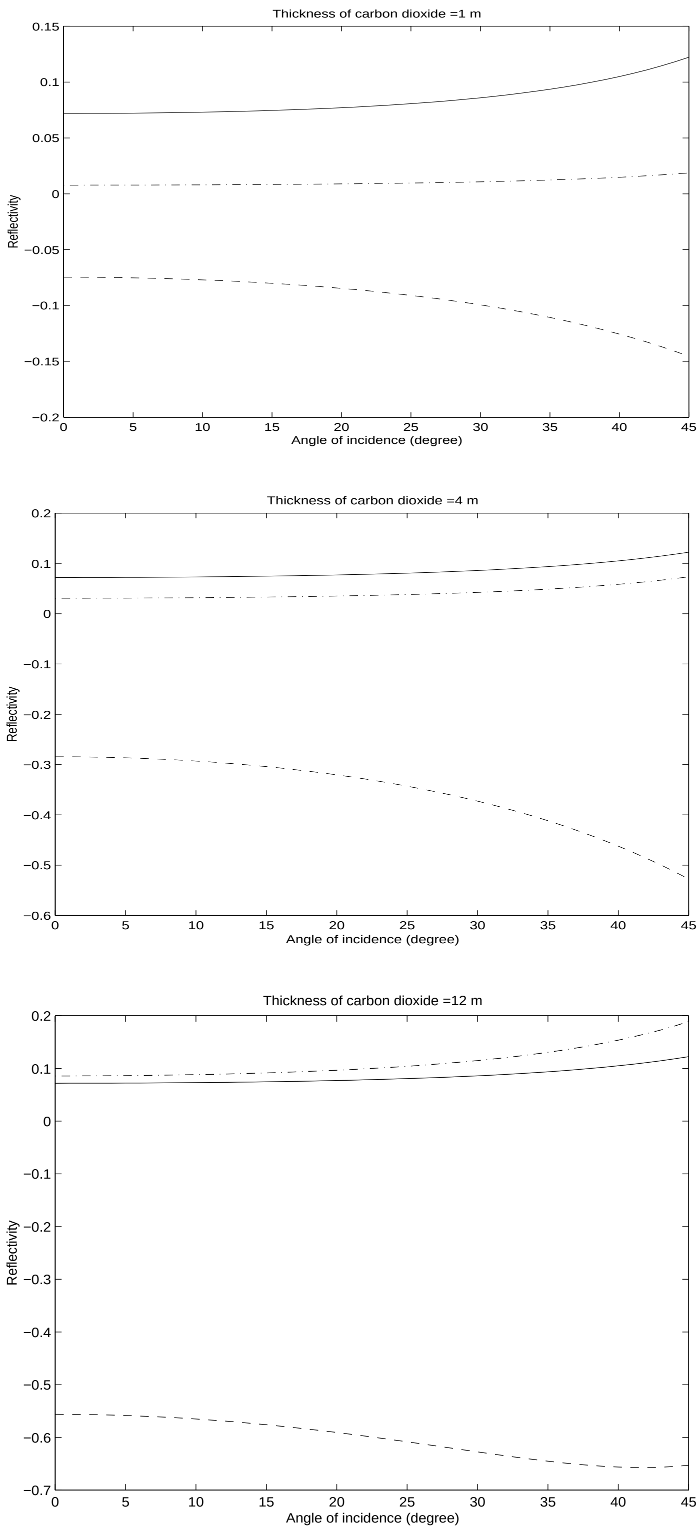

Figure 4.3: *Pseudo reflectivity in the difference data as a function of angle of incidence, at the* CO_2 *accumulation (dashed) and at bottom Utsira (dash-dotted) for layer thickness 1 m (top), 4 m (middle) and 12 m (bottom) respectively. The solid line indicates the original reflectivity at top Utsira.*

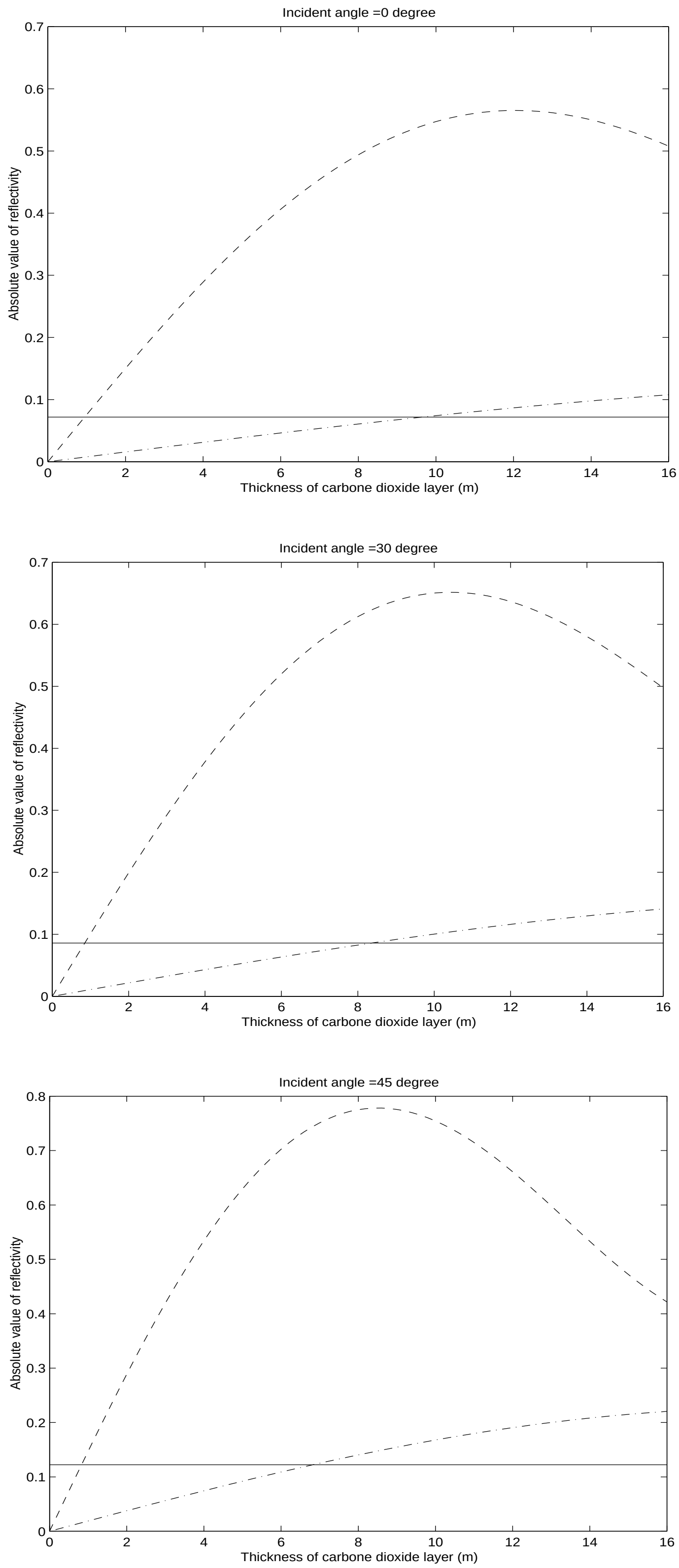

Figure 4.4: Pseudo reflectivity in the difference data as a function of CO_2 thickness, at the CO_2 accumulation (dashed) and at bottom Utsira (dash-dotted) for normal (top), 30 ^{o} (middle), and 45 ^{o} respectively. The solid line indicates the original reflectivity at top Utsira.

5. References

KORBØLL, R., KADDOUR, A., "Sleipner vest CO_2 disposal- injection of removed CO_2 into the Utsira formation". Energy Convers. Mgmt. Vol. 36 No 6 - 9., page 509-512, 1995.

LINDEBERG, E.G.B, "Escape of CO_2 from Aquifers". Energy Convers. Mgmt. Vol. 38 Suppl., page s229-s234, 1997.