

SIMULATION OF CO₂ DISTRIBUTION PATTERN IN AN UNDERGROUND CO₂ INJECTION PROJECTED CALIBRATED BY 3D SEISMICS

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ABSTRACT

In the ongoing aquifer CO₂ disposal project in the Sleipner license (North Sea), underground CO₂ is being monitored by time-lapse seismic. The CO₂ is being injected close to the base of a high permeable, highly porous sand unit, the Utsira Sand. In an iterative process between seismic surveys and reservoir simulations, a reservoir model featuring the major controlling heterogeneities has been developed. Well-data and seismic data prior to injection shows that the sand is divided by nearly horizontal, discontinuous shales. From the 3-D seismic image after three years of injection, strong reflectors can be interpreted as CO₂ accumulations identifying the major shale layers that control the vertical migration of CO₂ from the injection point to the top of the formation. By modelling this flow in reservoir simulations, it can be inferred that the CO₂ is transported in distinct columns between the shales rather than as dispersed bubbles over a large area. Improvement of the geological model increases the confidence of predictions based on simulation of the long-time fate of CO₂. A possible natural aquifer flow can have a pronounced effect on the location of CO₂ accumulations due to the relatively flat topography of the trapping shales. This effect has been quantified by simulation and this phenomenon was used to adjust the localisation of the CO₂ bubbles to better fit the seismic images.

INTRODUCTION

The study has three objectives:

- To provide information about the most likely distribution of the injected CO₂ prior to the first time-lapse seismic survey. This result formed the basis for the decision on when and how an optimal seismic survey should be obtained after injection had started.
- To mimic the observed CO₂ distribution after the first seismic survey in reservoir simulations by adjusting the reservoir properties that are most dominant with respect to CO₂ migration. This will provide geological input for the planning of next seismic survey.
- To use the new geological information in the construction of a larger reservoir model that can be used for modelling the final fate (> 10 000 year) of the injected CO₂.

GEOLOGICAL AND SEISMIC DATA USED AS INPUT FOR A RESERVOIR MODEL

Prior to injection a 3-D seismic survey of the Utsira Sand had been acquired. This provided the topography of the reservoir unit. The Top Utsira Sand is relatively flat, but exhibits some domal and anticlinal structures linked by saddles. The injection site is located below a dome with a diameter of approx. 1600 m and a height of approx. 12 m above its spill point.

The reservoir consists of an unconsolidated sand with permeability in the range $2 - 5 \cdot 10^{-12} \text{ m}^2$ (~2 - 5 Darcy) determined by laboratory measurements and well tests. Analyses of wireline-logs (Figure 1) and seismic data indicate that the sand is rather homogenous, but that the reservoir units contain numerous (up to 14) thin (usually below one meter in thickness) shale layers (Zweigel *et al.* 2000). These layers roughly follow the topography of the Top Utsira Sand, i.e. they have domal geometry above the injection site. Based on assumptions about depositional processes (partial erosion) and about post-depositional deformation (differential compaction), it is inferred that these shale layers are not fully impermeable. The shale layers can be correlated well between boreholes up to a few

hundred meters apart, but cannot unanimously be traced over larger distances. The seismic picture of the Utsira Sand prior to injection is also dominated by reflectors within the Utsira Sand that are qualitatively parallel to the reservoir top (Arts et al. 2000).

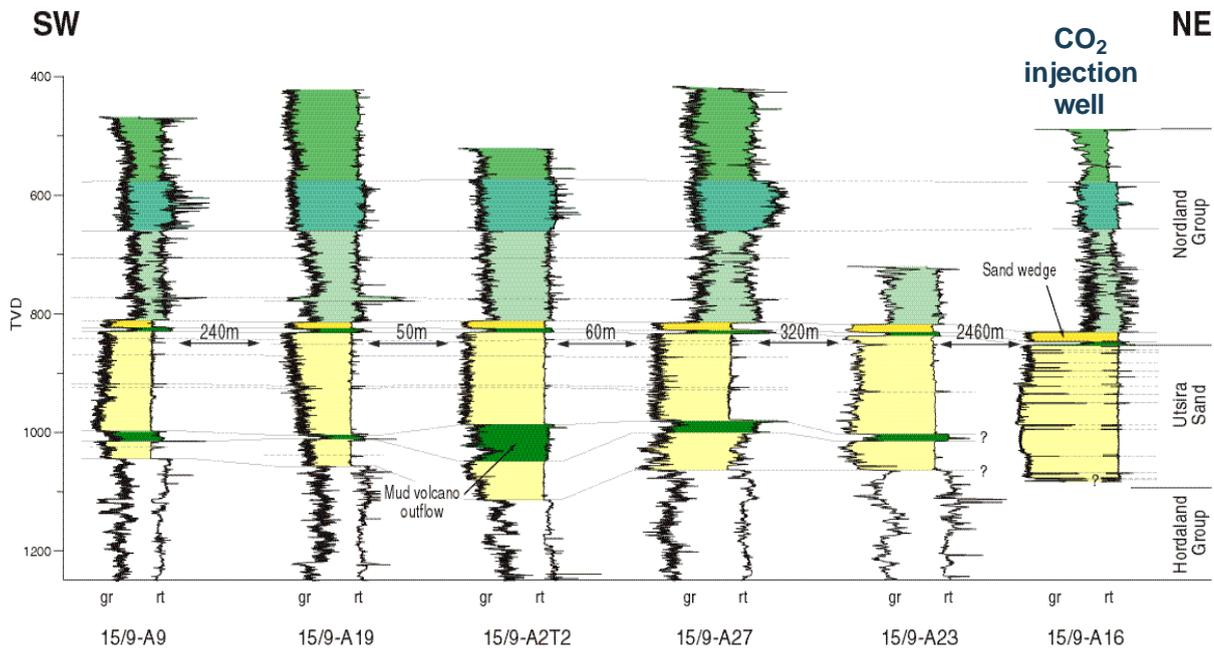


Figure 1 Examples of wireline well-logs through the Utsira formation. The Utsira sand (yellow) is homogeneous, but intersected by thin discontinuous horizontal shales.

MODELLING CO₂ DISTRIBUTION PRIOR TO TIME-LAPS SEISMIC SURVEY

All the following flow simulations were performed according to the method described by Lindeberg (1996) with the same simulator and same models for solubility, density, diffusion, and relative permeability. Only the reservoir model has been changed.

In the first approach a radial model consisting of a 160 m high cylinder with diameter of 1600 m was constructed. The top is a cone with a height of 12.5 m, corresponding to the dome at the injection site. The shales were represented as five equally spaced impermeable layers, parallel to the top and with apertures at 500 m intervals. A profile of the model is illustrated in Fig. 2, right corresponding to a cumulative injected amount of 2.2 million tonnes of CO₂ over a three-year period. The shales effectively attenuate the vertical migration by retaining CO₂ in bubbles on its way up to the top. The bubbles are up to 22 m thick and a seismic simulation of a corresponding CO₂ saturation profile indicated that it should be possible to map the accumulations by a seismic survey (Lindeberg et al. 1999). On this background a decision was taken to obtain a new 3-D seismic data set and in September 1999 the seismic survey around the injection point was performed. A profile obtained from a line in this new data set near the injection point is illustrated in Fig. 2, left, and the resemblance with the predictions from the simulations above were apparent, Fig. 2, right, e.g.:

- i) CO₂ has just reached the Top Utsira as predicted from the simulations
- ii) Large amounts of CO₂ are retained by layers parallel to the top similar to simulations.
- iii) The frequency, size, and spacing of these layers were approximately correct.

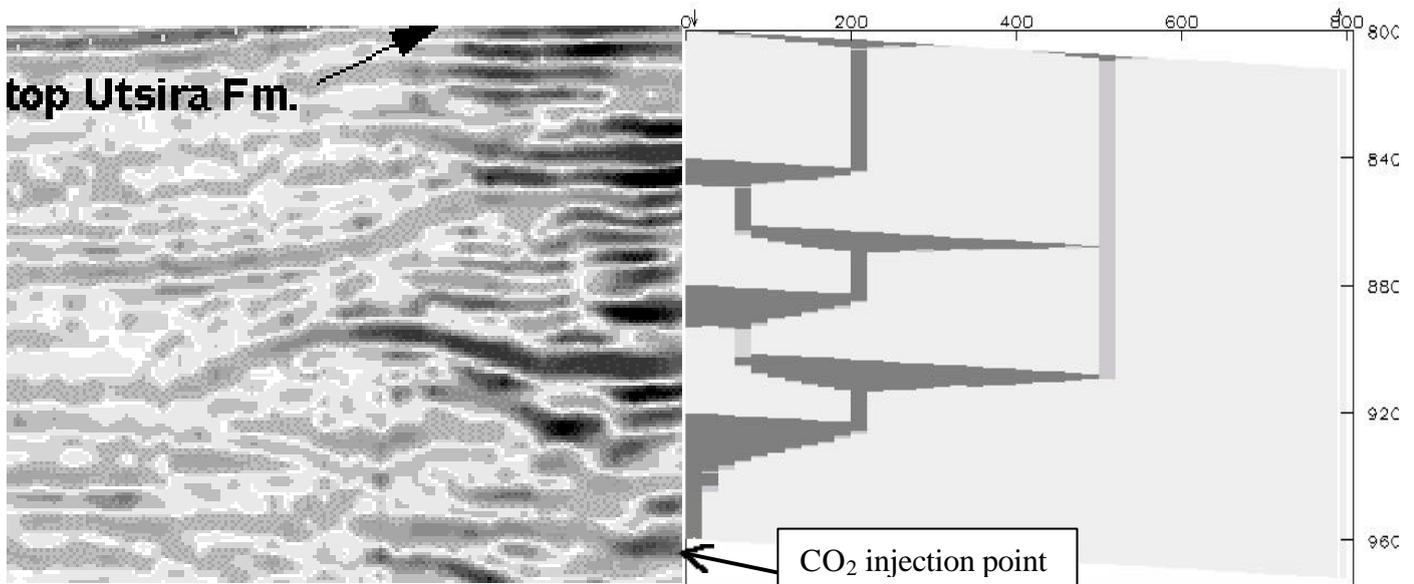


Figure 2 Left: Seismic image of a half-profile near the injection point after 3 years of CO₂ injection and back-to-back (right) the corresponding simulated saturation half-profile. The diameter of the model is 1600 m.

MODELLING CO₂ DISTRIBUTION AFTER TIME-LAPSE SEISMIC SURVEY

This new data set enables to update the reservoir model. Preliminary analysis of the time-lapse data set (Eiken *et al.* 2000) provided the location of the major seismic reflectors due to presence of CO₂. However, additional reservoir information can be extracted by indirect methods: the position, height, size and shape of the six large CO₂ accumulations can be mimicked in a reservoir simulation and thus provide information about the major transport mechanisms between the layers. For this purpose a 3-D corner point grid model of the reservoir was constructed, Figure 3. In this

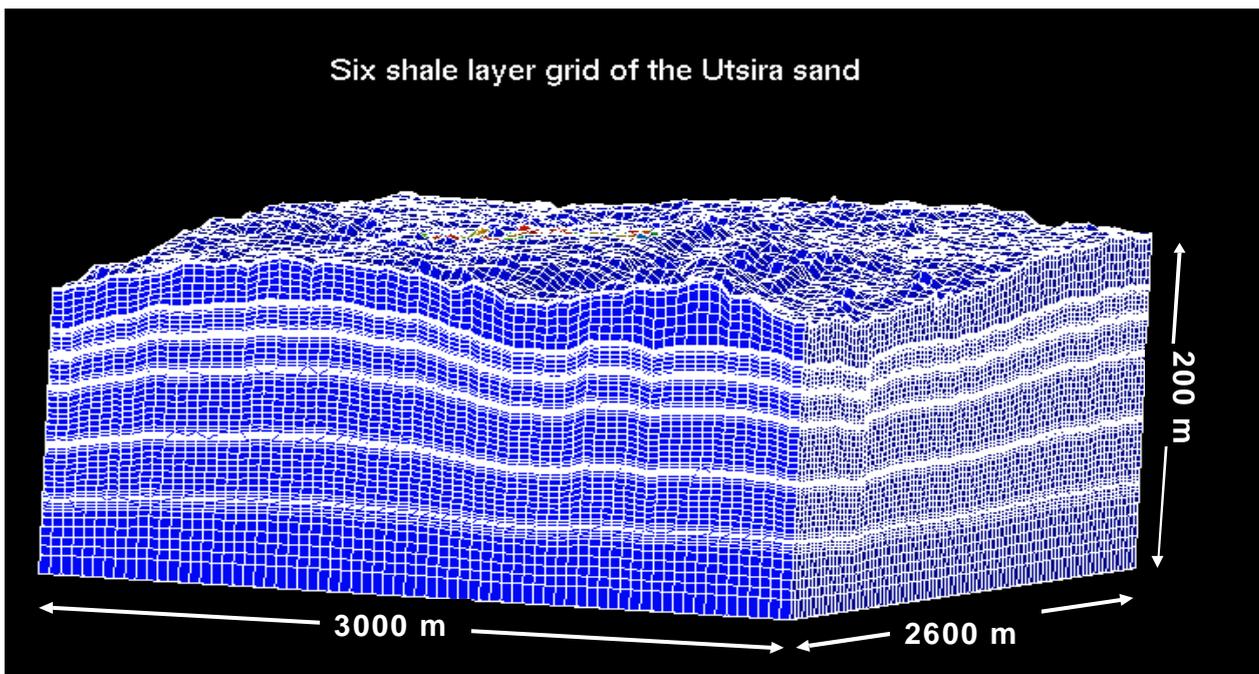


Figure 3. A 3D reservoir grid example used for simulation of simulations of CO₂ distribution. The number of grid blocks were 450 000 and 900 000 in different tests.

grid the top of the model was taken directly from the seismic interpretation of the formation (Arts *et al.* 2000). The intermediate CO₂ trapping horizons are parallel to the Top Utsira Sand in the higher part of the formation and are gradually flattening in its deeper parts. In the numerical grid, the topography of these layers is therefore represented as a linear combination of the top and what is assumed to be the floor of the formation. This geometry is kept constant in the simulations. There are two major possible mechanisms for transport from one layer to the next. The barrier layers are either semi-permeable allowing CO₂ to migrate through them as a dispersed flow, or the layers have holes, spill points or faults that conduct CO₂ in distinct columns. A quantification of the contribution from these two mechanisms will give a better understanding of the nature of the shales. The transmissibility of each shale layer was adjusted such that the resulting accumulations became similar in size to the corresponding seismic reflector while the transmissibility within each shale was kept constant. Also the permeability of the sand was kept constant in both horizontal and vertical direction ($5 \cdot 10^{-12} \text{ m}^2$). A comparison between seismic reflectors and simulated saturations is illustrated in Fig. 3.

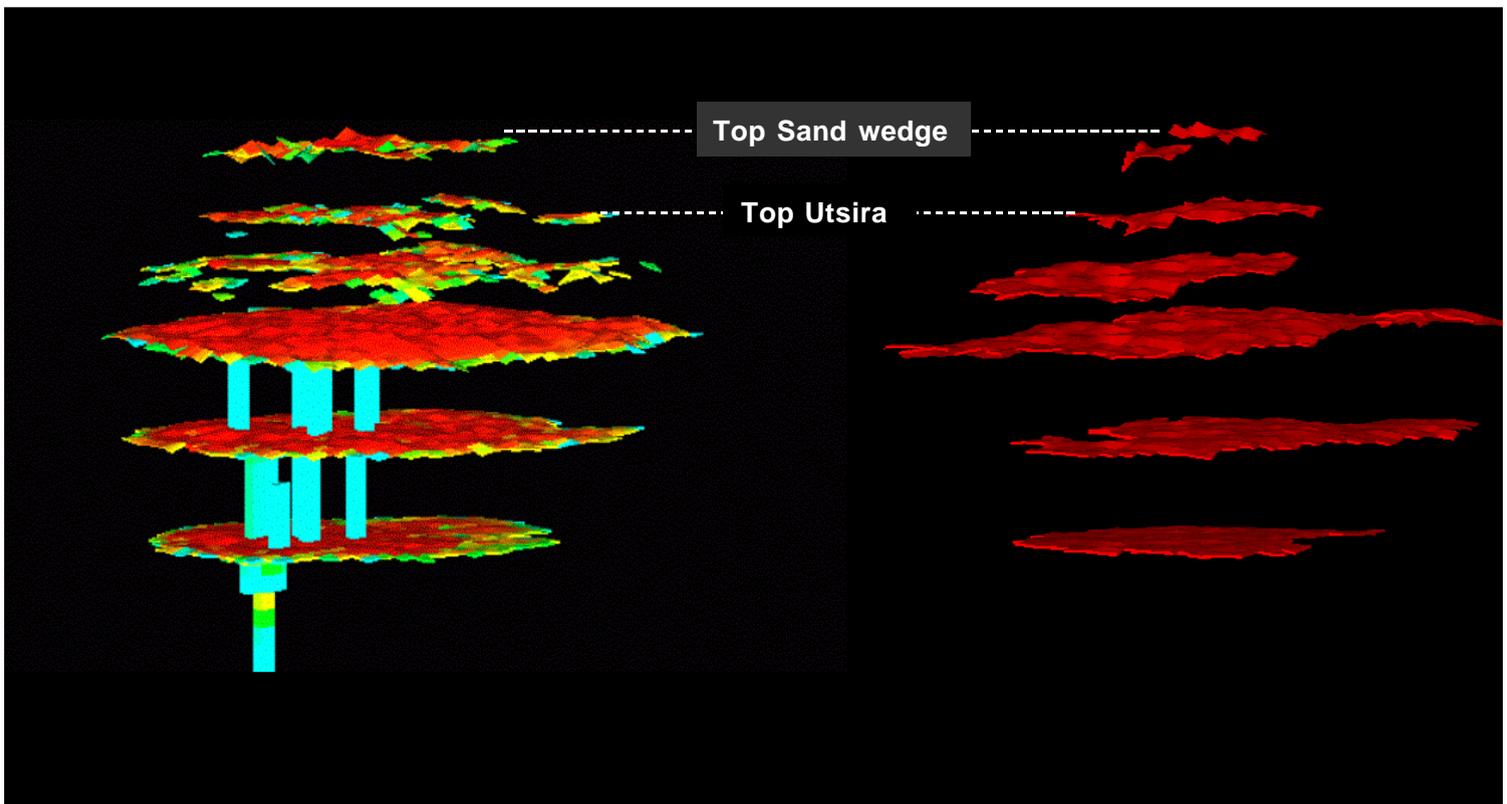


Figure 3. Simulated image (left) after three years of injection compared to seismic images (right). The largest bubble is approximately 1600 m long and 800 m wide. The other bubbles are approximately circular.

CO₂ is soluble in brine (approx. 50 kg/m³), but the amount of CO₂ dissolved will typically be small on short time-scale (<100 year) if very little water is in contact with CO₂. However, if the CO₂ is distributed under horizontal semi-permeable shales, more water will be in contact with CO₂, boosting the amount of CO₂ dissolved (Lindeberg, 1996). In the present case it was, however, not possible to achieve a good match with the seismic picture unless the solubility was reduced to 25%. This indicates that the migration between the layers does not take place by distributed percolation over a large area, which would yield too much dissolved CO₂. The migration must rather be controlled by localised spill points in the shales giving minimal contact

between CO₂ and brine. By suppressing solubility, the accumulations achieved approximately correct size and the CO₂ reached the top at the right time

EFFECT OF NATURAL AQUIFER FLOW

During the fitting process it was easier to obtain the correct size of the respective CO₂ bubbles than their location in the horizontal. They appear to be located ca 400 m too far in South-Southwest direction. A possible explanation may be that the constructed barrier topography does not exactly represent the shale topography in nature. This possibility has not been investigated further at the present, but this will be interesting to pursue when accurate topography interpretations for the barrier layers have been obtained from the base and time-lapse seismics.

Another explanation for the offset is the presence of natural lateral aquifer flow in the formation (hydrodynamic activity). The pressure gradient set up by such aquifer wind will cause the water/CO₂ contact to tilt and thus displace the CO₂ bubble. The corresponding phenomenon, tilted oil/water contacts, is well known in the oil industry (Dennis *et al.*, 1999). The effect of a possible wind was simulated and the displacing effect on the second lowest bubble is illustrated in Fig. 4. An aquifer wind of 3 m/year with 32° direction in the simulations was sufficient to displace the bubbles 400 m, to a location that corresponds better to the seismic image.

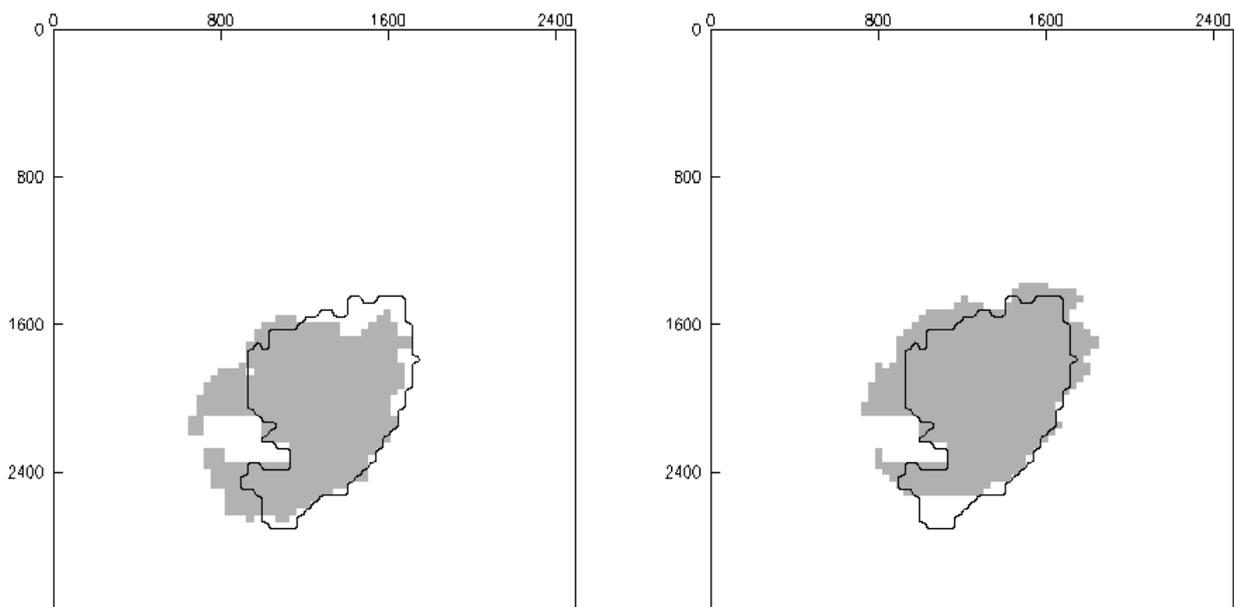


Figure 4: The CO₂ accumulation in the second accumulation is shown as a grey area without wind (left) and with a 3 m/year south-west aquifer wind (right). The corresponding seismic image is shown as a contour line

CONCLUSIONS AND DISCUSSION

By combining information from geology, seismics, and reservoir simulation it has been possible to construct a reservoir model of the Utsira Sand that includes the major properties controlling the migration of CO₂. The size, shape and localisation of the CO₂ accumulations seen on seismic images, can be mimicked by reservoir simulations based on this model.

The highly permeable Utsira Sand is divided by discontinuous shale layers sufficiently tight to retain migrating CO₂, but which contain localised permeable zones. CO₂ can leak through these

'holes' as large columns or curtains allowing a small contact area between brine and CO₂, thus limiting the dissolution of CO₂ in brine. A localisation of the major transport columns between the layers from detailed analysis of the 3-D seismic would further increase the confidence in this model.

The size of the CO₂ accumulations is probably underestimated in this interpretation because a certain minimum thickness of CO₂ will be required to give a detectable reflection. If the amount of "invisible" CO₂ is large, the evidence for the theory that CO₂ is transported between the shale layers mainly through high permeable spots will be further strengthened. The amount of hidden CO₂ can be quantified by seismic and reservoir simulations in up-coming studies.

ACKNOWLEDGEMENTS

We acknowledge funding by the SACS consortium (BP Amoco, ExxonMobil, Norsk Hydro, Statoil, European Union, and national agencies) and the Norwegian KLIMATEK program. Other partners in the project are BGS, BRGM, GEUS, IFP and NITG-TNO.

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