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PREDICTION OF CO_2 DISTRIBUTION PATTERN IMPROVED BY GEOLOGY AND RESERVOIR SIMULATION AND VERIFIED BY TIME LAPSE SEISMIC

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ABSTRACT

In the ongoing aquifer CO_2 disposal project in the Sleipner license (North Sea), underground CO_2 is being monitored by time-lapse seismic. The CO_2 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 CO_2 accumulations identifying the major shale layers that control the vertical migration of CO_2 from the injection point to the top of the formation. By modelling this flow in reservoir simulations, it can be inferred that the CO_2 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 CO_2. A possible natural aquifer flow can have a pronounced effect on the location of CO_2 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 CO_2 bubbles to better fir the seismic images.

INTRODUCTION

The study has three objectives:

- To provide information about the most likely distribution of the injected CO_2 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 CO_2 distribution after the first seismic survey in reservoir simulations by adjusting the reservoir properties that are most dominant with respect to CO_2 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 CO_2.

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 Utsira Sand, Fig. 1). 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 $2 - 5 \cdot 10^{-12}$ m^2 (~2 - 5 Darcy) determined by laboratory measurements and well tests. Analyses of wireline-logs and seismic data indicate that the sand itself is rather homogenous, but that the reservoir units contains 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

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are not fully impermeable. The shale layers can be correlated well between boreholes up to a few hundred meters apart, but can not 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).

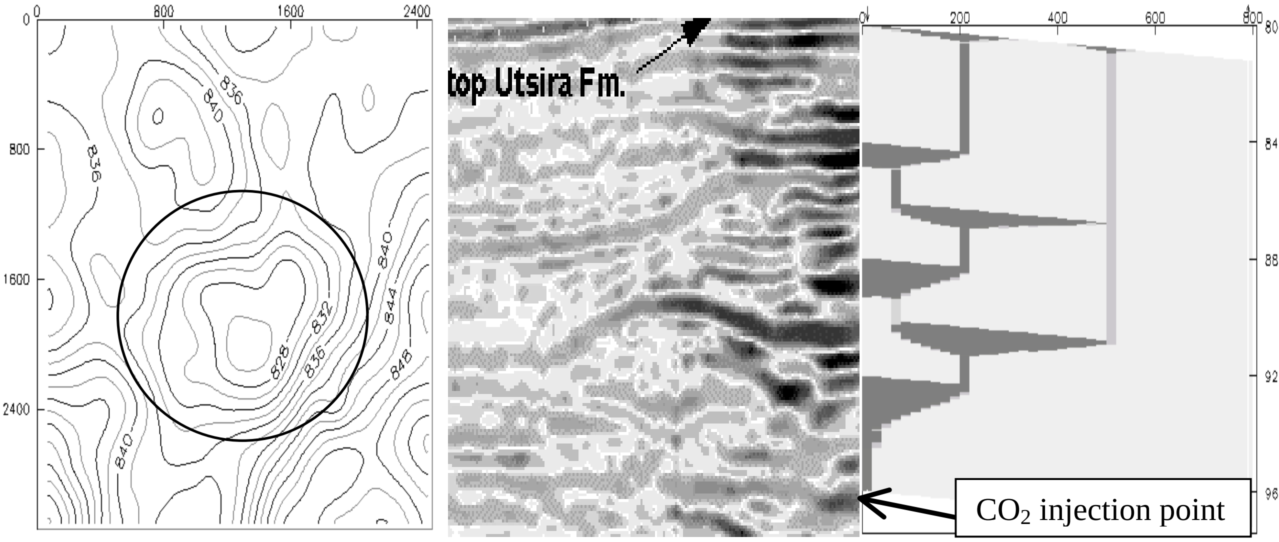

Figure 1: Left: A map of the Utsira cap with a circle (1600 m diameter) indicating the selected cylindrical domain that was object for the first simulations. Middle: Seismic image of a profile near the injection point after 3 years of CO_2 injection and back-to-back (right) the corresponding simulated saturation profile.

MODELLING CO_2 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. 1 (right) corresponding to a cumulative injected amount of 2.2 million tonnes of CO_2 over a three year period. The shales effectively attenuate the vertical migration by retaining CO_2 in bubbles on its way up to the top. The bubbles are up to 22 m thick and a seismic simulation of a corresponding CO_2 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, middle, and the resemblance with the predictions from the simulations above were apparent, Fig. 2 right, e.*g.*:

i) CO_2 has just reached the Top Utsira as predicted from the simulations
ii) Large amounts of CO_2 are retained by layers parallel to the top similar to simulations.
iii) The frequency, size and spacing of these layers were approximately correct.

MODELLING CO_2 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 CO_2. However, additional reservoir information can be extracted by indirect methods: the position, height, size and shape of the five large CO_2 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. In this grid the top of the model was taken directly from the seismic interpretation of the formation (Arts *el al.* 2000). The intermediate CO_2 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 CO_2 to migrate through them as a dispersed flow, or the layers have holes, spill points or faults that conduct CO_2 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 between of the sand was kept constant in both horizontal and vertical direction ($5 \cdot 10^{-12}$ m^2). A comparison between seismic reflectors and simulated saturations is illustrated in Fig. 3.

CO_2 is soluble in brine (approx. 50 kg/m^3), but the amount of CO_2 dissolved will typically be small on short time-scale (<100 year) if very little water is in contact with CO_2. However, if the CO_2 is distributed under horizontal semi-permeable shales, more water will be in contact with CO_2, boosting the amount of CO_2 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

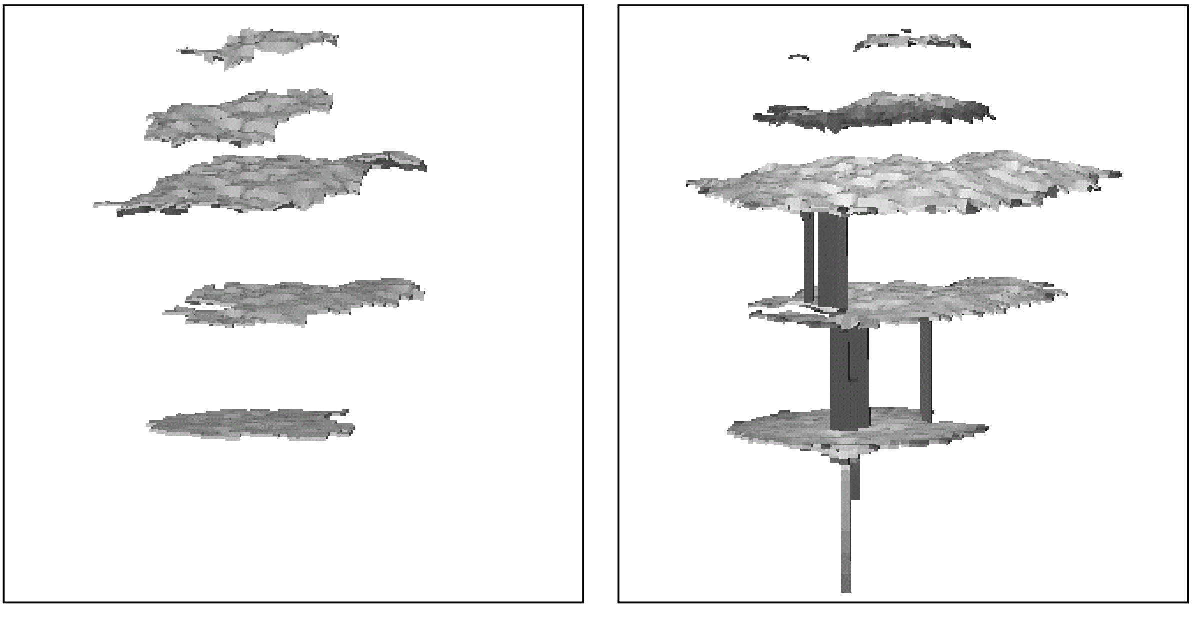

Figure 3: Seismic picture of CO_2 bubbles (left) compared with simulated CO_2 saturations after 3 years of injection

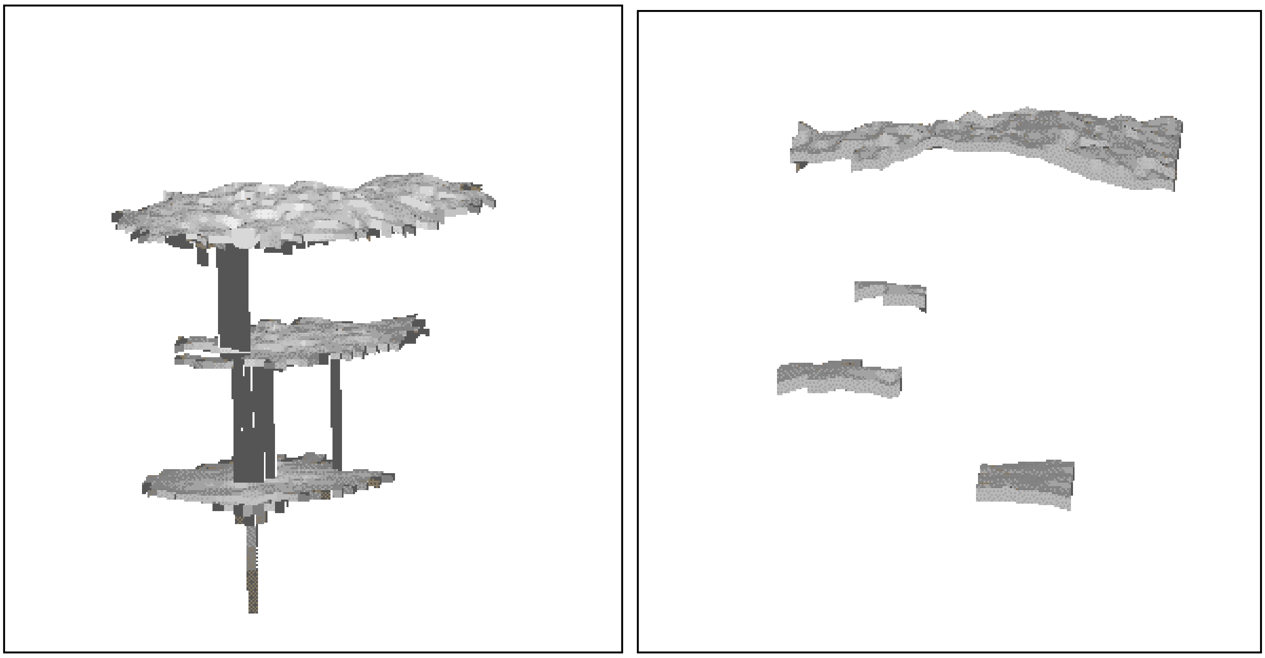

Figure 3: Left: Simulated CO_2 saturation after 3 years if the layers are semi-permeable. Too much CO_2 has been dissolved (38%). Right: Holes in the four lower layers, producing the pattern shown in Fig. 2

by distributed percolation over a large area, which would yield too much dissolved CO_2 (Fig. 3, left). The migration must rather be controlled by localised spill points in the shales giving minimal contact between CO_2 and brine. By suppressing solubility, the accumulations achieved approximately correct size and the CO_2 reached the top at the right time. The holes introduced in the model are illustrated in Fig. 3, right.

EFFECT OF NATURAL AQUIFER FLOW

During the fitting process it was easier to obtain the correct size of the respective CO_2 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/CO_2 contact to tilt and thus displace the CO_2 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.

GRID SIZE AND RESOLUTION

A compromise between the desire to model flow and phase phenomena with high resolution and the computing capacity has to be established. Too large grid blocks give excessive dissolution of CO_2 due to numerical dispersion. The practical upper limit for a 3-D grid is about one million grid blocks with the author's facilities. Simulation with different resolutions was used to study the

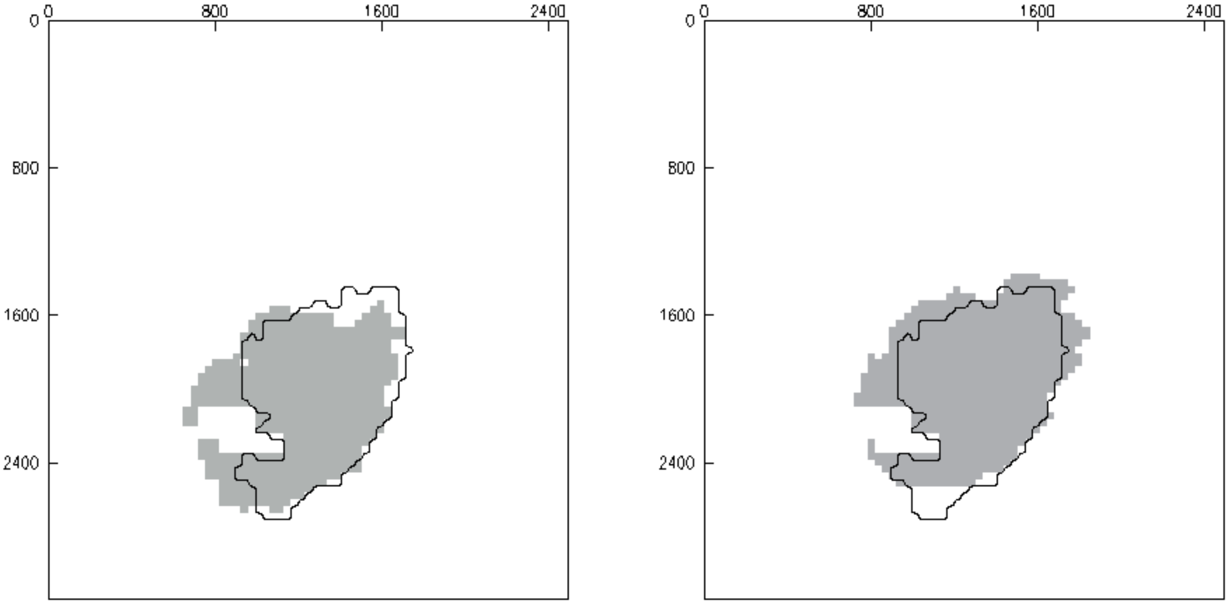

Figure 4: The CO_2 accumulation in the second accumulation is shown as a grey area without wind (left) and with a 3 m/year south-west aquifer wind (right). The corresponding seismic image is shown as a contour line

effect of the resolution. The number of grid blocks was varied between 108 000 and 860 000 to explore if the apparent dissolution of CO_2 would converge to a limit. The result is illustrated in Fig. 5 and shows that there is little effect to increase resolution more than to 430 000 grid blocks if the layers behave as semi-permeable barriers. The simulated solubility is more sensitive to increase of the resolution in horizontal direction than an increase in the vertical direction. The relation is not monotonous, but appears to converge. It must be emphasised that the result is specific to this particular problem. The optimal grid strongly depends on the geometry of the heterogeneities and on physical properties of the fluids.

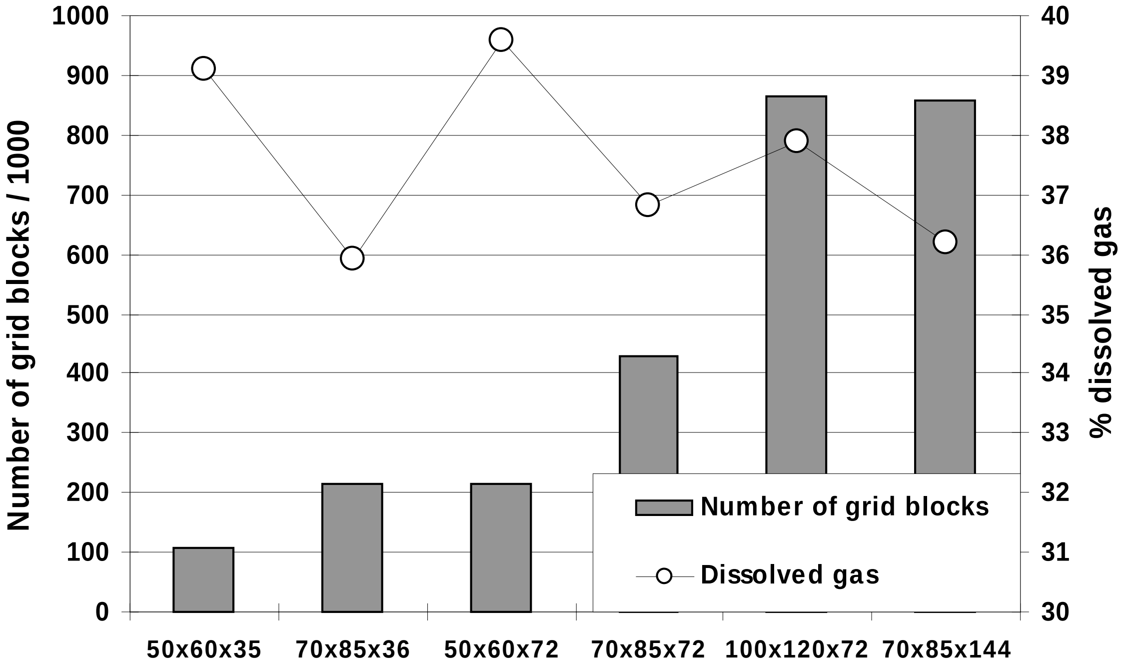

Figure 5: Effect of increased grid resolution on the apparent amount of dissolved CO_2.

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 CO_2. The size, shape and localisation of the CO_2 accumulations seen on seismic images, can be mimicked by reservoir simulations based on this model.

The high permeable Utsira Sand is divided by discontinues shale layers sufficiently tight to retain migrating CO_2, but which contain localised permeable zones. CO_2 can leak through these 'holes' as large columns or curtains allowing a small contact area between brine and CO_2, thus limiting the dissolution of CO_2 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 CO_2 accumulations is probably underestimated in this interpretation because a certain minimum thickness of CO_2 will be required to give a detectable reflection. If the amount of "invisible" CO_2 is large, the evidence for the theory that CO_2 is transported between the shale layers mainly through high permeable spots will be further strengthened. The amount of hidden CO_2 can be quantified by seismic and reservoir simulations in up-coming studies.

ACKNOWLEDGEMENTS

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