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Results and Experiences from the First Industrial-scale Underground CO_2 Sequestration Case (Sleipner Field, North Sea)

Background

CO_2 separated from natural gas produced at the Sleipner field in the northern North Sea (Norwegian block 15/9) is currently being injected into a saline aquifer, some 800 to 1000 m beneath the northern North Sea. Injection started in 1996 and shall last for 20 years at annual rates of approx. 1 million metric tons CO_2 (for a description of the injection facilities and of basic reservoir data refer to Baklid et al. 1996). An international research project, the Saline Aquifer CO_2 Storage (SACS) project, accompanies the ongoing injection. Its aims are (a) to determine the local and regional storage properties of the reservoir (the Utsira Sand) and its overlying seal, and to assess their suitability for CO_2 injection elsewhere; (b) to monitor the injected CO_2 by geophysical methods; (c) to simulate and predict the present and future CO_2 distribution by reservoir modelling; and (d) to develop a ‘best-practice’ handbook to guide future CO_2 injection projects. We report here results from areas (a) to (c).

Regional geology of the Utsira Sand and its storage potential

Based on an extensive regional seismic and wire-line log database, the reservoir unit, the Utsira Sand, has been re-defined and remapped. Several sand units of Miocene-Pliocene age in the northern North Sea can be distinguished from the Utsira Sand by seismic stratigraphic methods. Some of these units are possibly in hydraulic contact with the Utsira Sand and are likely to add to its storage potential. Occasional sand-rich prograding wedges at the basin margin, which underlie, overlie or are adjacent to the Utsira Sand, may provide undesired migration pathways that need to be assessed for each potential storage site.

The Utsira Sand covers an area of more than 2.6×10^4 km^2 and ranges in depth from about 550 to 1500 m (Figure 1a; Chadwick et al. 2000). It occupies two distinct depositional basins, which are likely to be in poor hydraulic contact. The maximum reservoir thickness is about 300 m (Figure 1b) and the estimated pore volume of the reservoir (excluding stratigraphically different, but possibly linked sand units) is 5.5×10^{11} m^3. Applying calculation procedures of Holloway (1996) to the Utsira Sand (see also below), this yields an estimated storage volume in topographically defined traps of approx. 6.6×10^8 m^3.

The succession above the Utsira Sand (the Nordland Fm.) is rather variable, but principally comprises prograding deltaic wedges of Pliocene age with general coarsening upwards trends from shales in the deeper, central parts of the basin to silt and sand in the shallower and more marginal parts. In the Sleipner area, the shale package is between 200 and 300 m thick, and its lower part consists of a shale drape, which separates the reservoir from the overlying prograding wedges.

Improved geological model for the Sleipner area

The Utsira Sand has a strongly varying thickness in the Sleipner area (block 15/9), ranging from ca. 50 m to slightly over 300 m. These variations are largely due to the presence of mud edifices (diapirs and volcanoes) at the base of the reservoir but also due to depressions of the reservoir top above the edifices as a consequence of their preferential compaction (Figure 2). Linked depressions of the

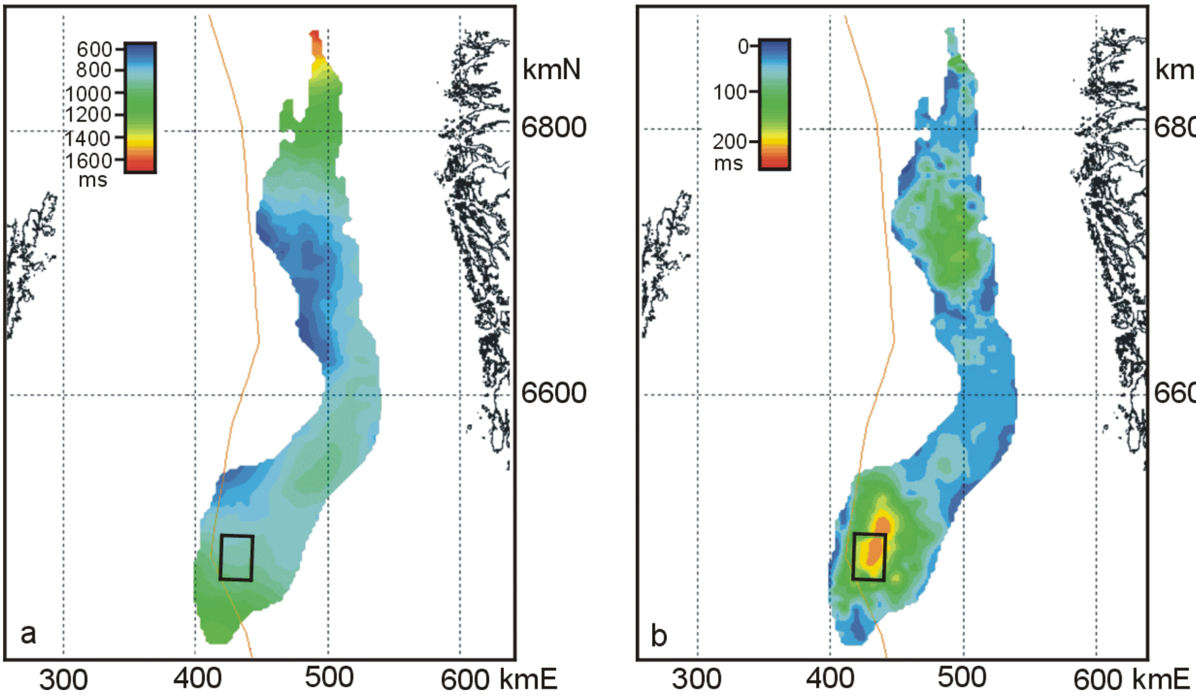

Figure 1: Preliminary maps of the Utsira Sand a) two-way travel-time map to top reservoir b) two-way reservoir isochore map.

reservoir top generate intervening domal structures, which are connected by saddle-shaped spill-pathways. The injection site is situated below a dome of approx. 1600 m diameter.

Previous interpretations, which served as input for pre-injection reservoir simulations, assumed homogeneity of the Utsira Sand. Re-interpretation of wire-line log and 3D seismic data showed that the reservoir unit contains several thin (approx. 1 m thick) shale layers which follow in their topography roughly that of the top Utsira Sand (Figure 2; Zweigel et al. 2000). These layers were interpreted to retard, but not to inhibit, buoyancy-driven upward migration of CO_2 from the injection site close to the reservoir base towards the reservoir top (Lindeberg et al. 2000). An approx. 5 to 7 m thick shale layer separates an eastward thickening sand wedge in the lower part of the Nordland Fm. from the Utsira Sands underneath. This sand wedge provides an additional reservoir for CO_2.

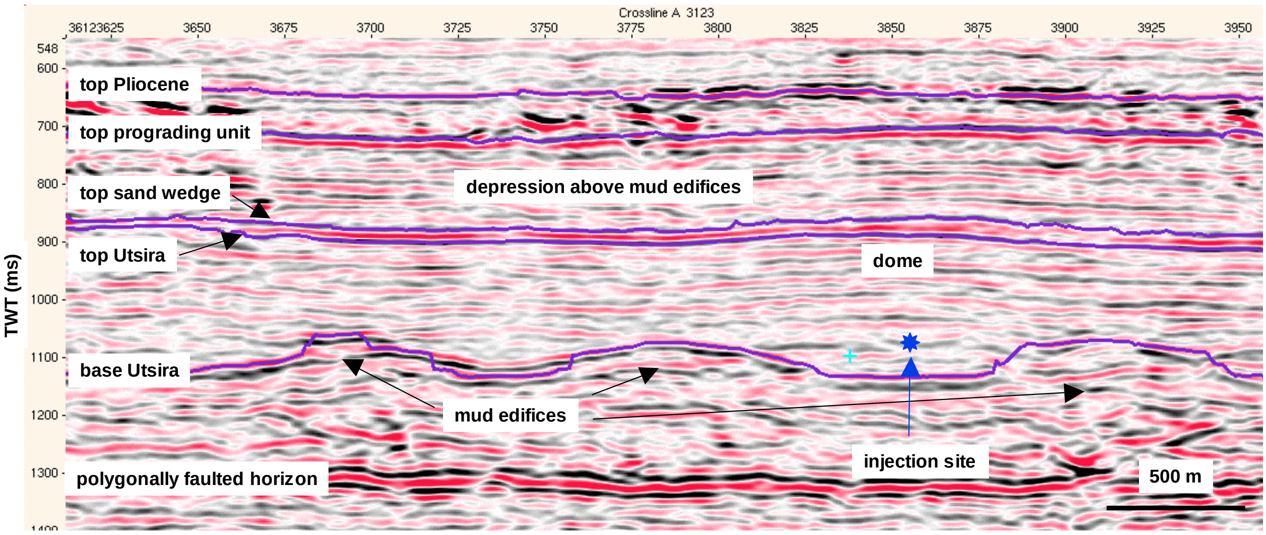

Figure 2: Seismic section through the injection site; survey ST98M11.

Analyses of Utsira Sand core samples yielded porosities ranging from 27 to 39 % and permeabilities ranging from 0.8 to 3 Darcy. Wire-line log data indicate strong lateral homogeneity of reservoir parameters, but limits of shallow gas indicators, which seem not to be structurally controlled, may signify some heterogeneity.

Maximum-case migration simulation

Topography-controlled, buoyancy-driven migration of CO_2 beneath top Utsira and within the sand wedge has been modelled employing a secondary hydrocarbon migration simulator, neglecting local storage beneath intra-Utsira shales and long-term solution and reaction processes (Zweigel et al. 2000; there, relevant input data are also listed). Assuming migration solely within the Utsira Sand proper, the projected 20 million metric Tonnes of injected CO_2 would migrate towards the NW with a maximum migration distance of no more than 12 km (Figure 3). The migration pathway from the present injection site contained 5 x 10^7 m^3 pore volume in traps within the studied survey area, providing storage space for almost twice the planned injection quantity. The simulation indicated a number of exploration and production wells (e.g. from platform Sleipner A) which may ultimately be reached by the CO_2.

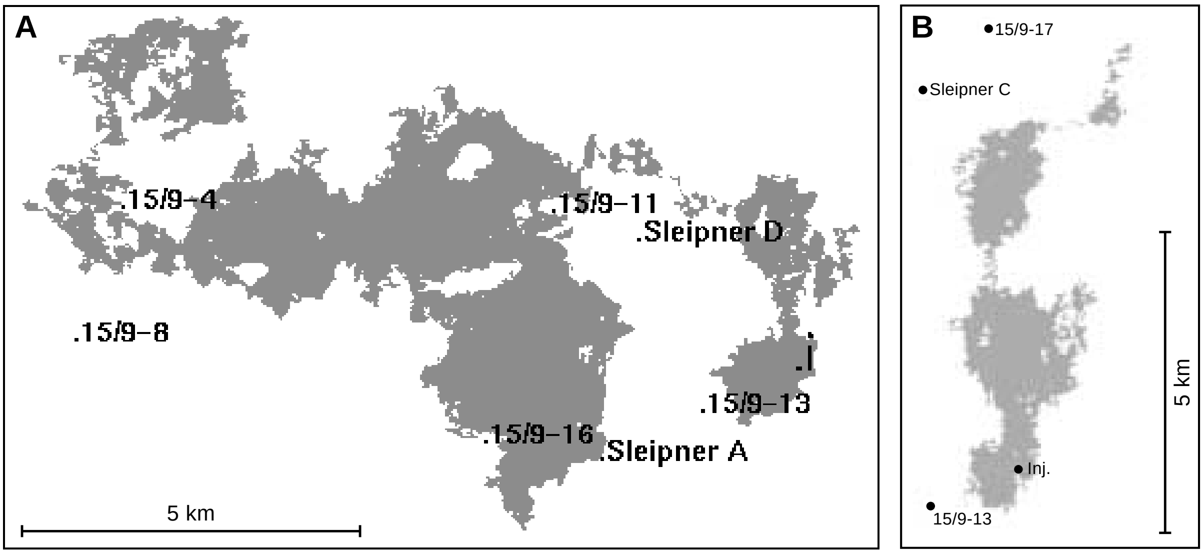

Figure 3: Areas of simulated CO_2 accumulations in topographically defined traps in the cases of migration beneath (a) top Utsira Sand and (b) top sand wedge. From Zweigel et al. (2000). i: injection site.

Migration within the sand wedge is predicted to occur in a northwestward direction. Up to 7.4 x 10^6 m^3 CO_2 can be trapped before the CO_2 leaves the studied area. This simulation highlights the effect of minor dip differences (typically 0.3º around Sleipner) between alternative migration barriers, and it points to the need to extend the studied area towards the E. The total storage volume to be accessed from the present injection site will depend on the partitioning between the two reservoirs. The total pore volume contained in traps in the studied survey area amounts to about 1.35 x 10^8 m^3, corresponding to 0.3% of the available pore space. Only a fraction of this could be accessed by an economically viable number of injection wells (e.g. 0.12% can be accessed from the present injection well). These numbers support the estimates of Holloway (1996) for the proportion of accessible pore space in traps.

Reservoir simulation

Based on the updated local reservoir model, simulations of the detailed distribution of CO_2 have been carried out employing a commercial simulator (Lindeberg et al. 2000). Prior to the time-lapse survey (see below), it was possible to predict the occurrence of CO_2 accumulations in layers underneath the intra-Utsira shale barriers. Further, it was predicted that CO_2 should reach the reservoir top at about the time of the time-lapse survey; this was in contrast to previous simulations based on a homogeneous reservoir model, which predicted arrival at the reservoir top a few months after injection start.

When the time-lapse seismic data (see below) became available, reservoir simulations were refined by matching predicted results to the observed distribution pattern with the aim to improve long-term predictions (Lindeberg et al. 2000, Van der Meer et al. 2000). It was possible to mimic the observed pattern in the simulations (Figure 4), if solution of CO_2 during the short time span available was assumed to be minimal. This requires most likely localised flow between the subsequent accumulation layers in contrast to distributed percolation through the barriers. Inclusion of a regional flow within the aquifer (see below) improved the match even more. The calculated density for CO_2 is approx. 700 kg/m^3.

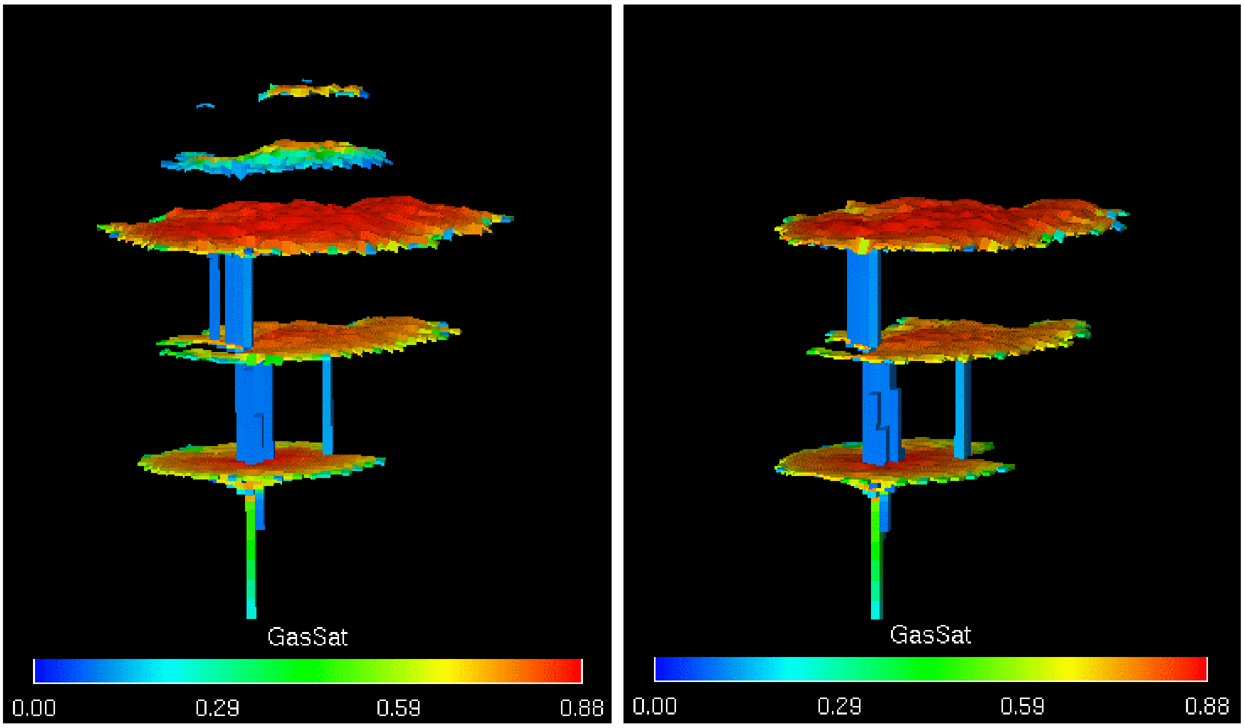

Figure 4: Simulated accumulations of free CO_2 underneath thin shale layers within the Utsira Sand at the time of the first time-lapse survey (Lindeberg et al. 2000). Left: Assuming localised leakage through shale layers; top accumulation at top Utsira Sand; results fit to results of seismic time-lapse survey (see below, Figure 5). Right: Assuming distributed percolation through the shale layers causes too much solution of CO_2 into formation water and too small and too few accumulations of free CO_2.

Time-lapse seismics

Feasibility studies based on the updated reservoir model and reservoir simulations indicated that monitoring of the injected CO_2 by seismics should be possible. A seismic time-lapse survey was accordingly acquired in early October 1999, after 3 years of injection. The time-lapse data show the occurrence of 'anomalies' (very strong amplitudes, most likely caused by CO_2) in several (ca. 5) layers within the Utsira Sand (Eiken et al 2000; Figure 5). This confirmed previous predictions (see above). The plan geometry of the accumulations follows roughly the closure topography of the dome and their lateral extent varies, reaching up to approx. 1.5 km diameter in NE-SW direction. The accumulation at the top Utsira is small, revealing that CO_2 had just reached this level. Two small anomalies above top Utsira indicate migration through the shale into the sand wedge.

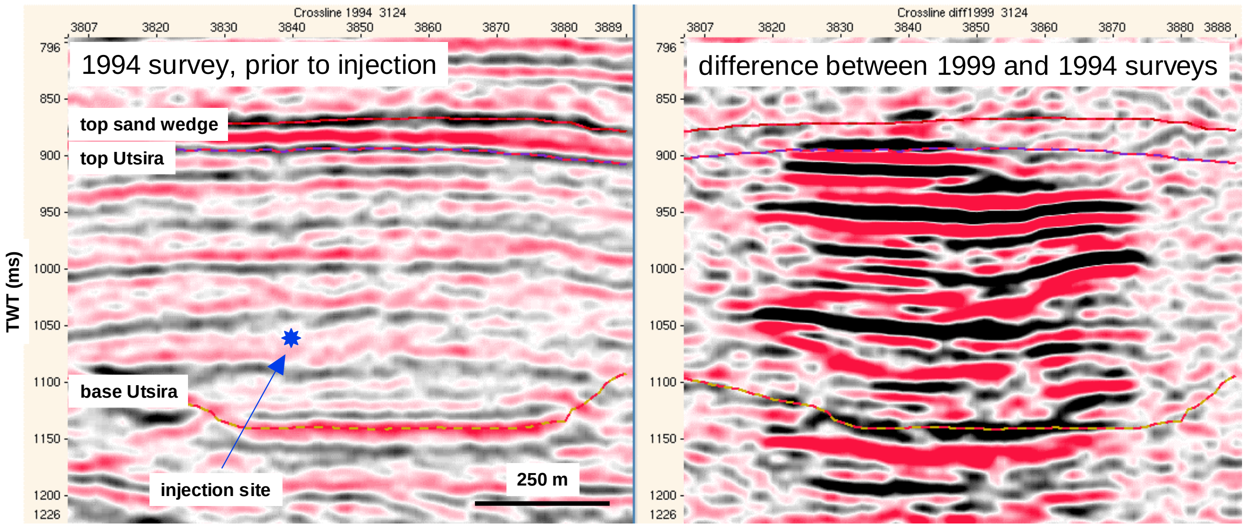

Figure 5: Seismic sections through the injection site. The time-lapse survey was shot in October 1999, when approx. 2.34 million metric Tonnes of CO_2 had been injected. Strong amplitudes in the difference cube (right figure) are interpreted to be due to CO_2 accumulations (those below the injection point are artefacts).

Natural fluid flow modelling

Regional fluid flow can influence the position and geometry (e.g. tilted base) of CO_2 accumulations, and it will determine the long-term migration of dissolved CO_2. Since very few data points on the pressure within the Utsira Sand were available, natural fluid flow has been simulated in a simplified 2D model, employing a commercial basin-modelling tool. The modelled section reaches down to the Zechstein salt. Fluid flow is driven by compaction and directed by the permeability distribution.

Four different models assuming different hydraulic connections (between the Utsira Sand and a sandy wedge at the basin margin, between the sandy wedge and the surface) and a different permeability distribution with the Utsira Sand have been calculated (Figure 6). All models yield present flow rates between 2 and 4 m/yr at the present injection site. Flow rates close to the pinchout of the Utsira Sand are higher and show a stronger dependence on the model parameters. These predicted higher flow rates need to be taken into account when assessing potential future storage sites closer at the basin margin.

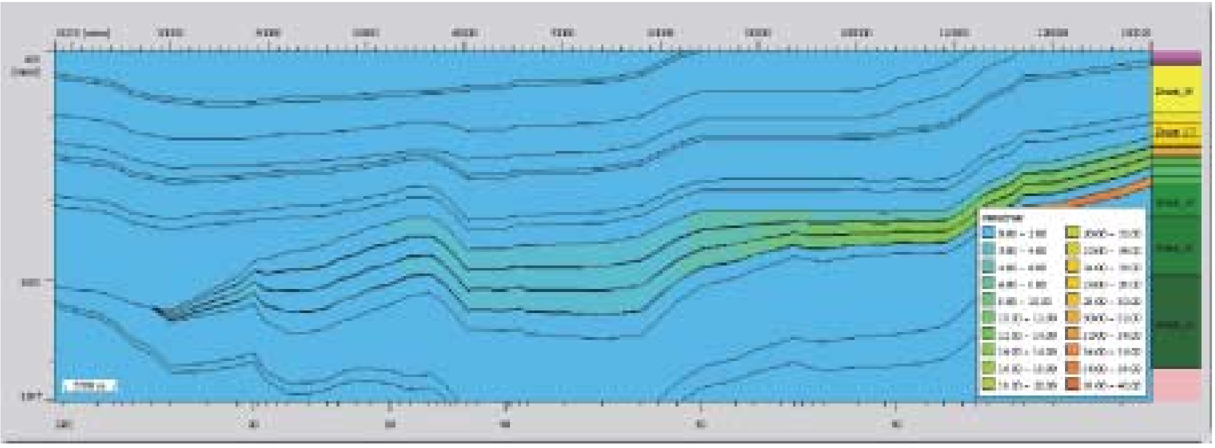

Figure 6: Flow simulation example. NNW towards right. Warm colours denote higher flow rates. Utsira Sand is the unit tapering out towards south and with high flow rates in the northern part.

Summary and outlook

The results of the SACS project so far have shown that prediction of the underground CO_2 distribution has been possible, given the adequately detailed geological model. Time-lapse seismic monitoring is feasible and helps to calibrate reservoir simulations which may improve the accuracy of long-term predictions. These results increase the confidence in the technology of underground CO_2 storage, a technology that has the potential to make an important contribution to reducing global CO_2 emissions.

Ongoing work within the SACS project includes predominantly quantitative analyses of time-lapse seismic data, investigations of geochemical aspects (solution of CO_2 and reaction with reservoir and/or cap rock), studies of the cap rock, assessments of non-seismic monitoring techniques, and further improvements of the reservoir simulators and the regional geological model. An additional time-lapse seismic survey is planned for 2001.

Acknowledgements

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More information about the SACS project can be found at http://www.ieagreen.org.uk/sacshome.htm and http://www.iku.sintef.no/projects/IK23430000/.