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PREDICTION OF MIGRATION OF CO_2 INJECTED INTO AN UNDERGROUND DEPOSITORY: RESERVOIR GEOLOGY AND MIGRATION MODELLING IN THE SLEIPNER CASE (NORTH SEA)

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ABSTRACT

Prediction of the distribution of CO_2 injected in the Sleipner area (North Sea) is a major topic of the international research project SACS. We report here a summary of detailed geological interpretations of the depository (the Mio-Pliocene Utsira Sands), based on seismic, wireline-log and sample data. We expect that CO_2 will ultimately migrate to the top of the Utsira Sands which is formed by the base of a Pliocene shale unit, or into an eastward thickening sand wedge closely above the base of the Pliocene shales. Therefore, and since CO_2 migration is primarily buoyancy driven, we consider the topography of the tops of these two alternative reservoirs to be of utmost importance for the medium-term migration pattern.

The two barrier surfaces were mapped at 3D seismic resolution and were used in various representations (different interpreters, time domain, depth domain etc.) as input for migration simulations employing the secondary migration simulator SEMI. Migration below the top Utsira Sands is predicted to take place in a north-westward direction and will probably be not more than ca. 12 km for a total injected quantity of 20 Mill. metric tons CO_2. Migration below the top sand wedge will take place in a north-eastward direction with the consequence that CO_2 will leave the studied area when up to 25% of the planned injection volume will have been trapped. Our simulation results highlight the importance of subtle topography differences (0.3º difference in regional dip between the two barrier horizons) on the migration pattern. The large migration distances and the necessary high topography resolution for storage sites in (shallow) aquifers demand modelling capacities not yet available with standard simulation tools.

INTRODUCTION

CO_2 separated from produced gas is being injected into an underground saline aquifer in the Sleipner area (northern North Sea) since 1996. This sequestration is the focus of the multi-institutional research project SACS (Saline Aquifer CO_2 Storage) which has the purpose to predict and to monitor the migration of the injected CO_2. Reservoir simulations show that the short-term migration pattern will be strongly influenced by reservoir inhomogeneities in the neighbourhood of the injection site (Lindeberg et al., this volume), and that the long-term fate of CO_2 depends largely on the mixing and solution in formation water (Lindeberg 1997). The medium-term (tens to hundreds of years) migration pattern is in the Sleipner case likely to be strongly dominated by the topography of the migration barrier at the reservoir top.

Migration simulation at all time-scales requires geological input data, ranging from reservoir properties (porosity, permeability) to the geometry of barrier and carrier horizons. Characterisation of the reservoir geology in the Sleipner case is accordingly a major part of the SACS project, and we will report a summary of the results up to now. Some of this geological data was then used for a simulation of the medium-term CO_2 migration pattern, showing that the hydrocarbon exploration tool SEMI can be used successfully to contribute to a safety evaluation of a CO_2-deposition site.

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RESERVOIR GEOLOGY

The CO_2 is injected close to the base of the Miocene-Pliocene Utsira Sands (Fig. 1). Wireline-log analysis (Fig. 2) shows the presence of several thin (usually less than 1 m thick) shale horizons within the Utsira Formation. These shales were predicted to affect CO_2 migration (Lothe & Zweigel 1999) which is confirmed by time-lapse seismic data (Arts et al. this volume). However, we expect the shale layers to contain fractures and holes, partly due to differential subsidence and partly due to erosion during deposition of the interlayering sands. The sands are weakly consolidated, highly permeable and have porosities ranging from 27 % to ca. 40 % (Lothe & Zweigel 1999, Holloway et al. 2000).

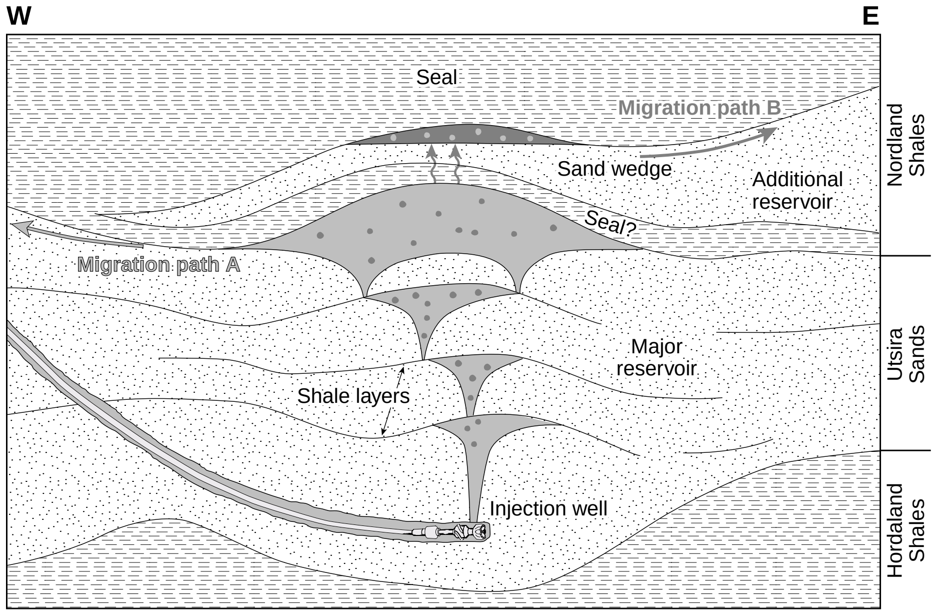

Figure 1: Schematic representation of the Sleipner storage system.

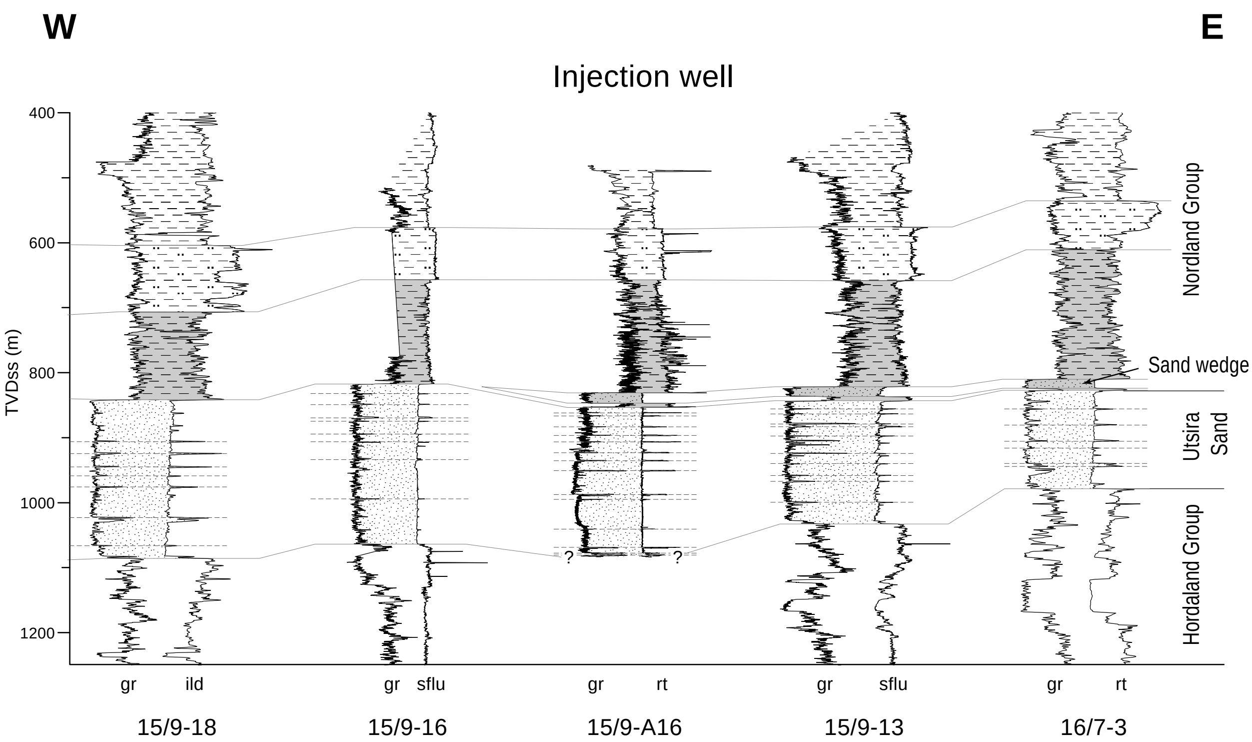

Figure 2:Wireline log profile through the Sleipner area, illustrating lithologies, the presence of shale layers in the Utsira Sands, and a sand wedge in the lowermost part of the Nordland Shales.

The Utsira Sands are overlain by the Pliocene Nordland Shales, which are several hundred meters thick and which are assumed to act as seal. The top of the Utsira Sands has been mapped based on wireline logs and 3D seismics in the injection area. This surface has a weak regional dip towards south, but has an irregular topography with several linked domal and anticlinal structures that are caused by subsidence anomalies (Fig. 3). These are due to mud mobilisation edifices at the base Utsira Sand. Above the top Utsira Sands, separated by a 5 m thick shale layer, exists an eastward thickening sand wedge (Fig. 1) identified in wireline-log data (Fig. 2) and mappable in the 3D seismic data.

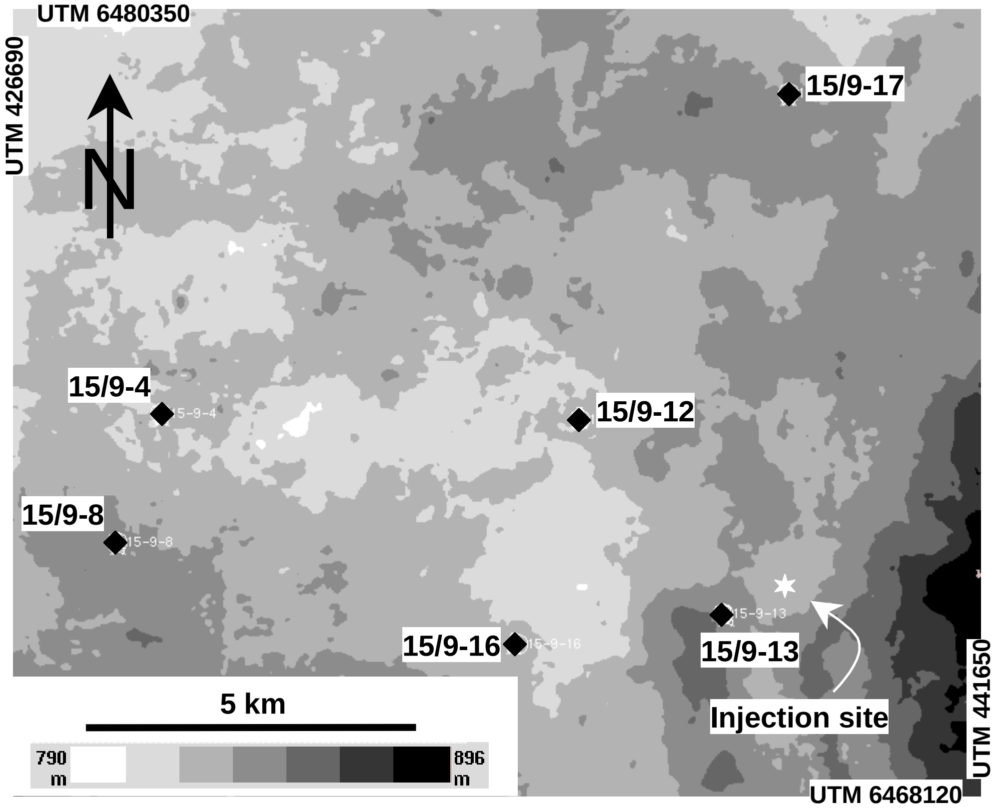

Fig. 3: Topography of the top Utsira Sand from seismic interpretation, strongly smoothed. Contour interval: 15 m. For a corresponding seismic section refer to Arts et al. (this volume).

MODELLING APPROACH

Gravity-controlled migration below barrier levels can be simulated employing SINTEF's in-house developed secondary hydrocarbon migration tool SEMI (Sylta 1991). The advantage of this tool over conventional reservoir simulators is its ability to incorporate reservoir geology (e.g. the topography of barrier horizons) at very high resolution. Our simulations neglected solution of CO_2 into water, leakage into the cap rock, changing pressure and temperature, and potential lateral porosity or permeability changes. The input data constant for all simulations are summarised in Tab. 1. In our approach, instantaneous migration after each injection interval was assumed, neglecting dynamic effects (e.g. non-horizontal bases of accumulations).

Simulations of migration below the top Utsira Sand were based on 4 different representations of the barrier topography (Table 2, cases U-1 to U-4), whereas the top of the sand wedge was used in two representations (Table 2, cases W-1 to W-2). In the top Utsira cases, we used no lower barrier for the accumulations, but in the sand wedge cases, the mapped base of the wedge was used as lower limit.

Table 1: Constant input data for all migration simulations

Injection rate	1 Mill metric tons / year
Injection duration	20 years
CO_2 density	700 kg/m^3
Utsira Sand porosity	30 %
Net/gross ratio	0.85
Model intervals (step duration)	2 years

Table 2: Barrier grid specifications.

Code	Interpreter	Interpretation Method	Domain	Cell size
U-1	PZ, AEL	manual & 2D autotrack	time	irregularly interpreted, 13 m * 13 m in sim.
U-2	RA	3D autotrack	time	13 m * 13 m
U-3	RA	3D autotrack	depth	13 m * 13 m
U-4	RA	3D autotrack	depth	50 m * 50 m
W-1	PZ	constructed wedge (shape from well data) over case U-4	depth	50 m * 50 m
W-2	PZ	manual & 2D autotrack	depth	13 m * 13 m

SIMULATION RESULTS

The simulation results of the final distribution of CO_2, after a total quantity of 20 Million metric tons injected (total volume: ca. $30 \cdot 10^6$ m^3 CO_2), fall into two major groups, each having only minor differences between the individual models:

(a) If the top Utsira Sand acts as a long-term barrier, migration occurs primarily north-westwards, reaching a maximum distance of ca. 12 km to the injection site (Fig. 4). This maximum distance depends strongly on the porosity and the net/gross ratio of the Utsira Sands and we rate the used values to be conservative estimates. We neglected, moreover, processes leading to a reduction of free CO_2 (solution, chemical reactions), and the modelled final migration distance should, thus, represent a maximum estimate.

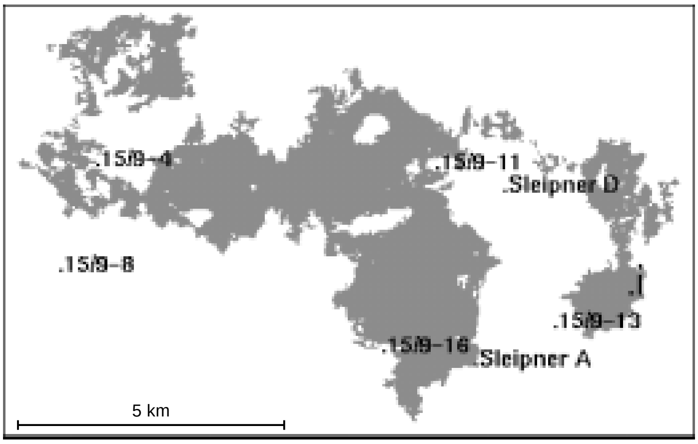

Figure 4: Final migration pattern below the top Utsira Sands after injection of $30 \cdot 10^6$ m^3 CO_2 (case U-3). Use well positions in Fig. 3 for orientation.'i': injection site position used (not fully correct). Intermediate steps and other cases are documented in Zweigel et al. 2000.

(b) If the 5 m thick shale layer above the top Utsira Sand leaks and CO_2 invades the sand wedge above, migration occurs primarily north- to north-eastward. A prediction of the maximum migration distance was not possible in that case because the CO_2 would then leave the area of the studied 3D seismic survey at a point ca 7 to 10 km NNE of the injection site. The volume stored within the modelled area is in the order of 4 to $7.4 \cdot 10^6$ m^3 CO_2, equalling to the total amount of CO_2 injected during 2.5 to almost 5 years.

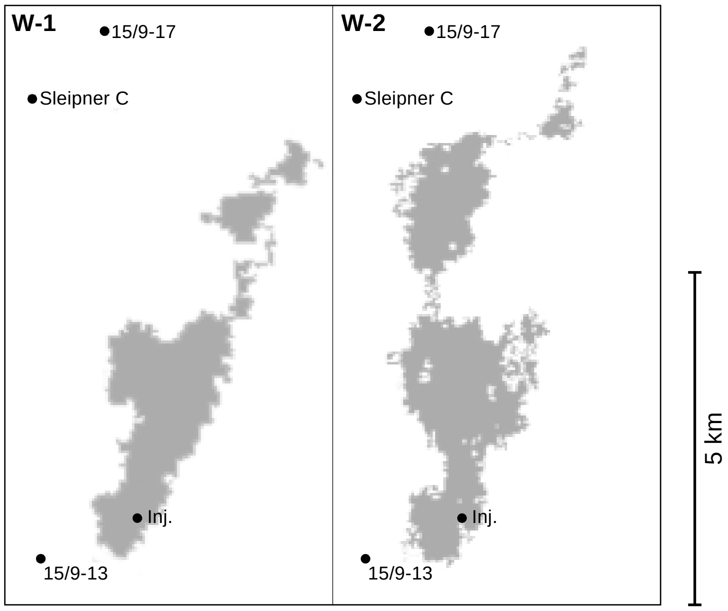

Figure 5: Final migration patterns below the top sand wedge after injection of 4 (case W-1) to $7.4 \cdot 10^6$ m^3 CO_2 (case W-2). Use well positions in Fig. 3 for orientation. 'i': injection site position used (not fully correct). Intermediate steps are documented in Zweigel et al. 2000.

DISCUSSION AND CONCLUSIONS

The simulations show that CO_2 injected in the Sleipner area will be confined to a relatively small area when migrating beneath the top Utsira Sands. There is, therefore, no risk that it will reach potential pathways to the sea floor in the UK sector further to the west. Further simulations (Zweigel et al. 2000) show moreover that the total trap volume along the spill path within the investigated survey is ca. 160% of the quantity planned to become injected, which provides a comfortable safety margin to compensate for uncertainties in input data. No risk assessment can be made yet for the case of migration within the sand wedge above the Utsira Sands. Our prediction on which exploration and production wells may become reached by CO_2 (Fig. 4 and 5, and Zweigel et al. 2000), can be used to assess the need for protective measures.

Preliminary interpretations of a time-lapse survey acquired in autumn 1999 (see e.g. Arts et al., this volume) suggest that a small fraction of CO_2 had already then migrated into the sand wedge. A quantification of the distribution between these reservoirs is, however, not yet possible. Such a partitioning would reduce the maximum migration distances and could, thus, increase reservoir safety. We expect that a planned 2^{nd} time-lapse survey to be acquired in 2001 will provide the possibility to quantify this partitioning. This may then form a base for decisions about further measures (e.g. extended seismic coverage towards East).

The simulated maximum migration areas will now be used within the SACS project to constrain the area for detailed, more realistic reservoir models, allowing to increase their resolution in depth.

More advanced migration simulations could also be achieved with SEMI, incorporating e.g. solubility, leakage, and permeability. We conclude that the use of such a hydrocarbon exploration tool can provide a valuable contribution to the safety assessment of a CO_2-deposition site.

The simulations show further that subtle differences between the barrier horizons used, such as a regional dip difference of 0.3º (i.e. ca. 4 m over a distance of 1 km), can have a decisive influence on the predicted migration pattern. The simulator must, thus, be able to honour small differences in depth and depth gradients. However, the demanded precision of depth grids is often clearly beyond presently available seismic resolution and seismic depth accuracy. This highlights the need to run a series of alternative models covering the uncertainty in input data.

The final area extent of CO_2 in underground storage sites can be large, and this will be especially the case for shallow aquifers with a nearly horizontal top (which may be preferable storage sites because the seal is not much deformed and might consequently be expected not to contain potentially leaking fractures). Realistic simulation of the fate of CO_2 in such sites demands, thus, large grid dimensions, in addition to a very high lateral and vertical resolution, the incorporation of reservoir heterogeneity, the representation of several temporary or final migration barriers within one model, and the need to run several alternative models. We rate this as not yet possible with existing reservoir simulation tools. The development of appropriate tools, based on available commercial reservoir simulators or on migration simulators, or on a combination of both, is consequently a major challenge to ensure safety and manageability of, and public confidence in, underground CO_2 storage projects.

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