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DEMONSTRATING STORAGE OF CO_2 IN GEOLOGICAL RESERVOIRS: THE SLEIPNER AND SACS PROJECTS

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ABSTRACT

At the Sleipner gas field in the North Sea, CO_2 has been stripped from the produced natural gas and injected into a sand layer called the Utsira formation. Injection started in October 1996, to date nearly 5 million tonnes of CO_2 have been injected without any significant operational problems observed in the capture plant or in the injection well. The Sleipner project is the first commercial application of CO_2 storage in deep saline aquifers in the world. To monitor the injected CO_2 a separate project called The Saline Aquifer CO_2 Storage (SACS) project was established in 1998.

As part of the SACS project, 3D seismic surveying has been used to successfully monitor the CO_2 in the Utsira formation, an industry first. Repeat seismic surveys have successfully imaged movement of the injected CO_2 within the reservoir. Reservoir simulation tools have been successfully adapted to describe the migration of the CO_2 in the reservoir. The simulation packages have been calibrated against the repeat seismic surveys and shown themselves to be capable of replicating the position of the CO_2 in the reservoir. The possible reactions between minerals within the reservoir sand and the injected CO_2, have been studied by laboratory experiments and simulations.

The cumulative experiences of the Sleipner and SACS projects will be embodied in a Best Practice Manual to assist other organisations planning CO_2 injection projects to take advantage of the learning processes undertaken and to assist in facilitating new projects of this type.

INTRODUCTION

The offshore gas field Sleipner, in the middle of the North Sea, has been injecting 1 Mt CO_2 per year since September 1996 [1]. The CO_2 is injected into a salt water containing sand layer, called the Utsira formation, which lies 1000 meter below sea bottom. During 1998, a group of energy companies together with scientific institutes and environmental authorities in Norway, Denmark, the Netherlands, France and the UK formed the Saline Aquifer CO_2 Storage (SACS) Project Consortium and started to collect relevant information about the injection of CO_2 into the Utsira formation and similar underground structures around the North Sea. The SACS project involves a multidisciplinary approach. The different scientific disciplines involved in the project include: geology, geochemistry, geophysics and reservoir engineering/simulation.

In 1999 the SACS (Phase 1) project (supported under the European Commission's Thermie Programme) started monitoring the CO_2 behaviour and established a baseline by shooting a first 3D seismic survey [2]. The Phase 1 Project was extended to SACS2 in 2000 again with European Commission (EC) support. The SACS2 project, which will run until early 2003, continued the work undertaken in Phase 1 with further repeat 3D seismic surveys completed to track the fate of the injected CO_2. In addition, it is using the seismic data to verify available models and tools (originally developed for hydrocarbons and water) that have been applied to a CO_2 and water system. The major difference being that CO_2 is soluble in water and methane is not.

The goal of the SACS2 project is to develop a consensus about the monitoring results and validity of available models and tools. To develop such a consensus involves close co-ordination between the scientific institutes involved in the project. The cumulative experiences of the SACS projects will then be embodied in a Best Practice Manual to assist other organisations planning CO_2 injection projects to take advantage of the learning processes undertaken and to assist in facilitating new projects of this type.

The paper aims to set out the main findings of the SACS projects by first discussing the properties of the Utsira formation, it then sets out to answer a series of questions that could be posed by briefly outlining the work of the various scientific disciplines involved in the project. The detailed results from these aspects of the project are the topic of several separate papers at this conference.

THE GEOLOGY OF THE UTSIRA FORMATION AND ITS CAP ROCK

The Utsira formation is a highly elongated sand reservoir, extending for more than 400 km from north to south and between 50 and 100 km from east to west, with an area of some 26 100 km^2. The top Utsira formation and surface generally varies relatively smoothly, mainly in the range 550 to 1500 m, but mostly from 700 to 1000 m. There are two main depocentres. One is in the south, around Sleipner, where thicknesses range up to more than 300 m. The second depocentre lies some 200 km to the north of Sleipner. There the Utsira formation is locally 200 m thick, with an underlying sandy unit adding further to the total reservoir thickness [3].

The cap rock succession overlying the Utsira formation is rather variable, and can be divided into three main units, the lower, the middle and the upper seal. The lower seal extends well beyond the area currently occupied by the CO_2 injected at Sleipner and seems to be providing an effective seal at the present time (Figure 1). Empirically, therefore, the caprock samples suggest the presence of an effective seal at Sleipner, with capillary leakage of CO_2 unlikely to occur [3].

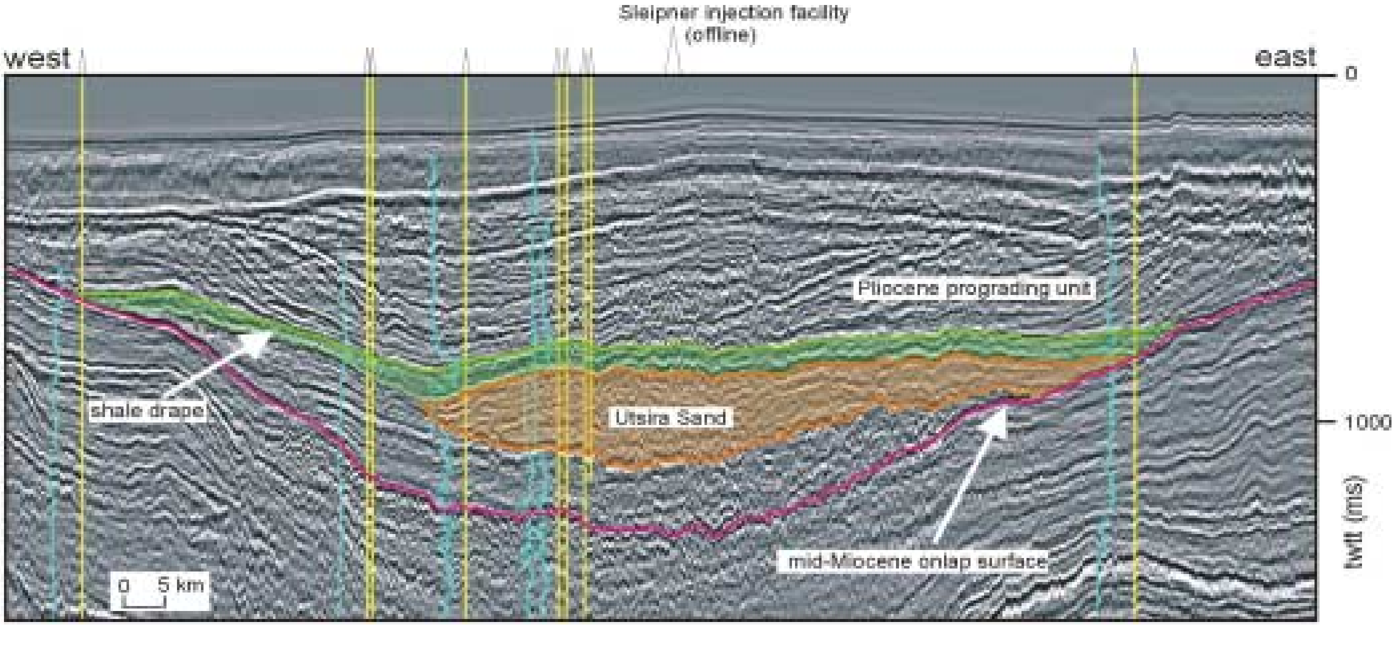

Figure 1: Regional Seismic line through Southern Part of Utsira Formation
(Courtesy of British Geological Survey and Schlumberger Geco-Prakla

Macroscopic and microscopic analysis of core and cuttings samples of the Utsira formation show that it consists of a largely uncemented fine-grained sand, with medium and occasional coarse grains. Porosity estimates of the Utsira formation core based on microscopy range generally from 27% to 31%, locally up to 42%. Laboratory experiments on the core give porosities between 35 and 42.5% [3].

WHAT HAS BEEN LEARNT FROM THE SACS/SACS2 PROJECTS

The findings to date from the SACS/SACS2 projects are summarised in the following sections. Other papers to be presented at the conference will give more detailed results on the findings of the project researchers.

What has happened to the injected CO_2?

The major success of the SACS/SACS2 projects has been the demonstration that conventional time lapse seismic data can be a successful monitoring tool for CO_2 injected into a saline aquifer. Even with the CO_2 not in a gaseous but in a supercritical phase it has been shown that CO_2 accumulations with a thickness as low as about one metre can be detected by causing significant, observable and measurable changes in the seismic signal. The seismic surveys have clearly shown how the injected CO_2 behaves in the underground saline aquifer [4, 5]. It is this major effect on the time lapse seismic signal of relatively thin CO_2 accumulations that has built our confidence that any major leakage into the overlying cap rock succession would have been detected. So far, no changes in the overburden have been observed at Sleipner.

The repeat seismic surveys have clearly shown that the injected CO_2 moves, due to buoyancy effects, from the injection point and accumulates under the overlying cap rock, which was expected (Figure 2).

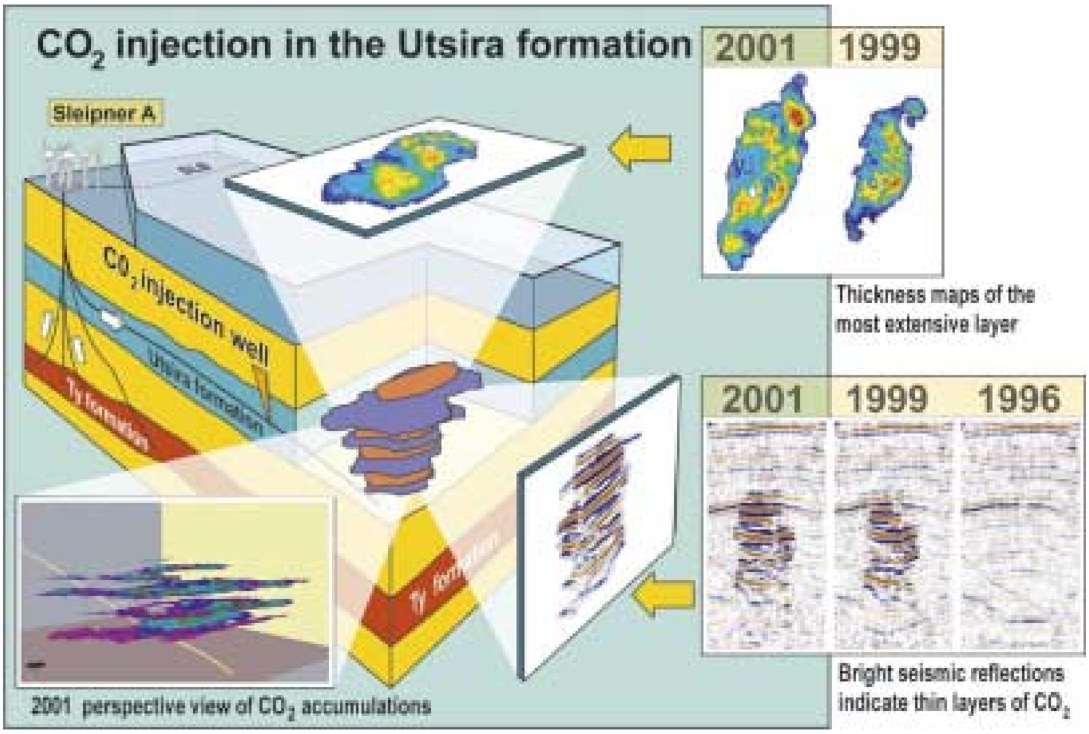

Figure 2: Diagrammatic Representation of Repeat Seismic Surveys and Position of Injected CO_2

The presence of thin shale layers has radically affected the CO_2 distribution in the reservoir, with CO_2 migrating laterally for several hundred metres beneath the intra-reservoir shales (Figure 2). It is likely that in the longer term this dissemination of CO_2 throughout the reservoir thickness (rather than just being concentrated at the top) may allow more efficient dissolution of CO_2 and effectively increase the reservoir capacity above the minimum value defined by the volume of the top reservoir traps. Estimates indicate that there is sufficient structural closure at the top of the Utsira Sand to trap 20 MT of CO_2 within 12 km of the injection site.

Close to the base of the lower seal to the east of the injection point is a confined sand wedge up to 50 m thick. Indications, based on the 2001 seismic results suggest some of the injected CO_2 has migrated into this reservoir. The implications for migration of the CO_2 into the sand wedge are twofold. First trapping of CO_2 in the sand wedge, as well as beneath the top of the Utsira formation, will also increase the overall storage capacity significantly. Second, partitioning of CO_2 between the top Utsira formation and the sand wedge will decrease migration distances in both cases, essentially confining the CO_2 more closely to the injection point.

How does the Injected CO_2 Behave Within the Reservoir?

If the injected CO_2 reacts with certain non-carbonate calcium-rich (or even Fe and Mg rich) minerals this could trap the CO_2 as a solid carbonate precipitate. The process is known as mineral trapping and essentially the CO_2 will be immobilised for geological time periods. However, geochemical experiments and modelling studies have shown that the sand within the Utsira formation showed only limited reaction with CO_2. Most reaction occurred with carbonate phases (shell fragments), but these were a very minor proportion (about 3%) of the overall solid material [6]. Silicate minerals showed only slow and minor reaction. Overall, it would appear that mineral trapping of the CO_2 in the Utsira formation will not trap a significant proportion of the injected CO_2 within the Utsira formation. This does not imply that mineral trapping in other reservoirs will occur to a significant extent.

One key area that still remains unresolved is the behaviour of CO_2 with the reservoir seal (both cap rock and borehole cement seals). Now that a core sample has been taken the geochemical experiments to assess the impact of CO_2 on the cap rock integrity can begin in earnest.

Because mineral trapping will not occur significantly, dissolution of the CO_2 is a more important factor in the storage of CO_2 in saline aquifers. The solubility of CO_2 in brine at the temperature and pressure of the Utsira Formation is approximately 53 kg/m^3. Dissolved CO_2 could, therefore, potentially be a significant contribution to CO_2 storage in an aquifer. Reservoir simulations have indicated up to 18% of the injected CO_2 could become dissolved in the by the lifetime of the project.

What is the long term Fate of the Injected CO_2?

Based on the positive experiences gained from developing a reservoir simulation model that has successfully history matched the repeat seismic surveys [7,8], a reservoir model was then developed to allow long term predictions of the fate of the injected CO_2 to be made. In the model the cap rock is assumed to provide a capillary seal for the CO_2 phase preventing upward migration, but allowing molecular diffusion of CO_2 through the overlying strata. The results of the simulations show that most of the CO_2 accumulates in one bubble under the cap seal of the formation a few years after the injection is turned off. The CO_2 bubble spreads laterally on top of the brine column and the migration is controlled by the topography of the cap seal only. The model indicates that diffusion of CO_2 from the gas cap into the underlying brine column will have a pronounced effect. The brine on top of the column, which becomes enriched in CO_2, is denser then the brine below which sets up convectional currents maintaining a large concentration gradient near the CO_2/brine interface, enhancing the dissolution of CO_2. The initial simulations indicate that bubble will reach a maximum size after probably less than 300 years. After this time, dissolution is the dominating effect on bubble extension and the bubble will gradually shrink and finally disappear around 4000 years.

Upward molecular diffusion of CO_2 through the water-saturated overlying shales has also been considered in the simulation studies, because this can potentially represent an escape path for CO_2 into the atmosphere. Along this pathway injected CO_2 will not reach the sea floor until several hundred thousand years after the end of injection.

Are there alternative monitoring options?

As indicated earlier, repeat seismic monitoring has been successfully used at Sleipner to follow the progress of the injected CO_2 in the reservoir. Seismic monitoring, however, is not an inexpensive operation. The SACS2 project has evaluated a number of other options for monitoring, namely pressure monitoring and observation wells. Both these techniques are used for monitoring conventional natural gas storage projects in Europe.

If we consider the key points of the Utsira formation namely; that it highly permeable with an enormous pore volume compared to the injection and that he cap rock has shallow domal structures that free gas columns of only 15-25 m. Because of these features, it has been concluded that monitoring of the storage reservoir pressure is not a key issue as the shape and size of the storage reservoir cap and spill points will only lead to minor pressure build up. Therefore, the pressure increase in the aquifer due to CO_2 injection is expected to be in the sub bar area, i.e. far below estimated limits to avoid mechanical failure or gas penetration through undisturbed cap-rock.

The costs for installation of monitoring wells are considered to be very high at Sleipner. Statoil have estimated that the cost of drilling and completion of a monitoring well only i.e. without an extensive logging and sampling program will cost in the range of MNOK 55 – 60 (M€ 32.3 -38.7). A combined characterization and permanent monitoring well could cost MNOK 70 (M€ 45). The high cost is associated with the rig rates and the time needed to drill the well, typically a 4 week campaign.

Since pressure monitoring is unlikely to be practical at Sleipner it is not considered an ideal case for active monitoring wells, because of the high costs involved. In addition, there are no upper aquifers that could be used for leakage monitoring.

WHAT NEXT

As indicated earlier, whilst the SACS2 project is nearing its conclusion, there are a number of initiatives that will extend the work that SACS has started and have continued through into SACS2.

The key results of the SACS2 project will be presented at this conference in a series of papers by the research groups involved in the project. Indeed, every effort has been made to ensure that the results from SACS/SACS2 have been presented to the public at conferences and at specialist events such as SPE, AAPG, EUG, both in Europe and the USA.

The complied learning from the SACS/SACS2 projects will be made available in the public domain in the form of a Best Practise Manual, which will be available later this year. The aim of the manual is to describe what was done, what has been learnt, what went well and where the perceive gaps in knowledge or data are. The objective of the manual, is to assist the development of new CO_2 storage projects through knowledge sharing and help them to build on the experiences and lessons learnt in pioneering projects such as SACS.

The manual is based entirely on the experiences of monitoring the CO_2 sequestration operation at Sleipner. When considering its application to other potential sequestration sites, it is important to bear in mind that the Earth's subsurface is an extremely variable natural system and its properties are highly site specific. Thus, the importance of some of the issues and procedures highlighted in the manual will vary between sites and, as new potential sites and sequestration concepts are investigated, they may throw up issues not considered important at Sleipner. This means that the manual should not be regarded as a set of standard procedures for the investigation or monitoring of a potential CO_2 sequestration operation.

The SACS2 project (due to end in April 2002) will now be extended until December 2002, due to additional support funding being available. The extension project will focus on a number of key issues, as yet unresolved in the project, which include:

- Detailed characterisation of the cap rock core sample that has now been taken at Sleipner,
- Geochemical investigations of the potential interaction between CO_2 and the cap rock,
- Detailed mapping of the Sand wedge area to assess impacts of CO_2 migration e.g. on storage capacity and migration pathways.

In addition, a gravity survey of the Utsira Formation will be undertaken. Gravity monitoring is seen as a complementary monitoring technique to time lapse seismic. It is thought that this monitoring method might be most effective deployed above the bubble and might give early warning of cap rock breaching. Also, it offers potential to verify the mass of CO_2 injected and confirmation of CO_2 density that will assist the reservoir simulation activities. It is expected that the results from the gravity survey will become available in late early 2003.

The work, howeve,r will not stop at the end of December 2003, because a new EC supported project, called CO2STORE, will extend the study of the Utsira Formation beyond 2003. The project will have two focuses, which are:

- To extend the work on the Utsira formation to investigate the long term fate of the injected CO_2 and evaluate other monitoring techniques, hopefully that are more cost effective that repeat seismic surveys.
- Apply the knowledge gained in SACS/SACS2 to develop site specific plans for CO_2 storage operations, elsewhere in Europe, both on and offshore

CONCLUSIONS

The Sleipner project is without doubt a world-leader being the first of a kind commercial CO_2 injection project. Such projects are necessary to prove that CO_2 capture and storage is a technically feasible and effective method for greenhouse mitigation. To gain international acceptance as a mitigation option, it must be demonstrated that CO_2 storage is both safe and has a low environment impact. The work that has been undertaken in SACS/SACS2 has shown that the injected CO_2 can be monitored within a geological storage reservoir, using seismic surveying. The geochemical and reservoir simulation work have laid the foundations to show how the CO_2 has reacted and what its long term fate in the reservoir will be, initial indications suggest several thousand years at least. Subsequent work in the following years will reinforce these initial findings that CO_2 storage is a practical and safe mitigation option that should be accepted internationally. It is hoped that the new CO2STORE project will assist in developing new opportunities for CO_2 storage in geological reservoirs in Europe.

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REFERENCES

1. Baklid, A, Korbøl, R. and Owren, G., (1996) SPE 36600, Denver, Colorado, USA.
2. Gale, J.J.et al, (2001), Environ. Geoscience, 8, 3, September
3. Chadwick, R.A. et al, (2000), Proceedings of the 5th International Conference on Greenhouse Gas Reduction Technologies, CSIRO, Collingwood, Australia
4. Arts, R., et al (2000), Proceedings of the 5th International Conference on Greenhouse Gas Reduction Technologies, CSIRO, Collingwood, Australia
5. Arts R., et al (2002) Proceedings of the 6th International Conference on Greenhouse Gas Reduction Technologies, Elsevier, London, UK.
6. Pearce, J.M., et al (2000), Proceedings of the 5th International Conference on Greenhouse Gas Reduction Technologies, CSIRO, Collingwood, Australia
7. Lindeberg, E., et al. (2000), Proceedings of the 5th International Conference on Greenhouse Gas Reduction Technologies, CSIRO, Collingwood, Australia
8. Meer, L.G.H. van der, et al Proceedings of the 5th International Conference on Greenhouse Gas Reduction Technologies, CSIRO, Collingwood, Australia