MANAGEMENT REPORT NO 1

CONTRACT N° : **ENK6-1999-00014**

PROJECT N° :

ACRONYM : **SACS2**

TITLE : **Saline Aquifer CO2 Storage**

PROJECT CO-ORDINATOR : **Statoil**

PARTNERS : **BP, ExxonMobil, Norsk Hydro, Vattenfall, BGS, BRGM, GEUS, IFP, SINTEF, NITG-TNO, IEA GHG, GECO**

REPORTING PERIOD : **FROM 1 April TO 30 June 2000**

PROJECT START DATE : **1 April 2000** **DURATION : 24 months**

Date of issue of this report : 8 September 2000

Project funded by the European Community under the 'Energie' Programme (1998-2002)

1. Technical Overview

Highlights from the period of report no 1:
Kick-off was at a Technical Session and Steering Committee Meeting in Stavanger 12. – 13. April 2000. The delayed start-up (1 April), caused some delay in re-mobilising the work groups after SACS project ended by New Year. Detailed work plans have been established and agreed between the different parties participating in the Work Packages.
First processing and initial interpretation of the 1999 3D seismic survey has been finalised and data transferred to institutes involved in WP Geophysics.

Important result: A worlds first!
This produced the world's first seismic image of CO_2 injected for storage in an aquifer ever. Earlier the very possibility to map the CO_2 by seismic had been debated among specialists. Now it has been proven!
This picture of the "world's first" was published as cover picture on the IEA Greenhouse Gas R&D Programme's "Annual Report 1999"

9 papers based on SACS results have been prepared and presented at international conferences; at the EAGE, Glasgow, at SEG, Calgary and 7 at the "5.Greenhouse Gas Technology", Cairns.

1.1 Summary of Objectives

The goal of the project:
Beginning in 1996, 1 million tons of CO_2 per year has been stored at the Sleipner Field in the North Sea. This is the first case of industrial scale CO_2 storage in the world. Being the first case, careful monitoring is necessary of the behaviour of the CO_2 storage facility - a thick saltwater-bearing sandstone at a depth of approximately 1 kilometer. Data will be collected to model and verify the distribution of the CO_2 'bubble' for three years, and methods will be demonstrated for prediction of the destiny of the CO_2 thousands of years into the future.

In addition to demonstrating the long term feasibility of storage of CO_2 in the Sleipner field case, it is a particular aim of the project also to provide a solid scientific documentation of CO_2 storage as a method. This may be applied in other geographical areas, and in other industries such as power generation.

Expected Results:
*A best-practices-manual comprising evaluation procedures on the feasibility of CO_2 storage in other geographical areas or large point sources in other industries.
* The project will generate a working methodology for evaluation of subsurface CO_2 storage from a technical and an environmental point of view, in order to satisfy authorities and the general public as to the feasibility, safety, and reliability of the CO_2 storage process.

The project consists of these Work Packages (WP):

WP 1 – Geology	lead by BGS
WP 2 – Reservoir Simulation	lead by SINTEF
WP 3 – Geochemistry	lead by BRGM
WP 4 – Monitoring Well Asses.	lead by Statoil
WP 5 – Geophysical Monitoring	lead by TNO
WP 6 – Reports & "Best-Practice."	lead by Statoil
WP 7 – Petro-Acoustic…	lead by IFP
WP 8 – Base Interpretation	lead by Geco
WP 9 – Time Lapse 1 Interpret.	lead by Geco
WP 10 – Time Lapse 2 Interpret.	lead by Geco
WP 11 – Synchronisation Res.Sim.	lead by Geco
WP 12 – Steering Committee	lead by Statoil

1.2 Technical Progress and Main Results

WP 1 – Geology lead by BGS and supported by GEUS and SINTEF

Summary
The following work has been carried out in the reporting period:

- Task 1.3 Stratigraphy and Structure of Greater Sleipner Area - Seismic and well data loaded. Interpretation of the Utsira Sand in the 'Greater Sleipner' area completed. Task completed.
- Task 1.4 Characterise Caprock – Preparatory work has commenced, mostly related to obtaining additional rock samples.
- Task 1.6 Determine Natural Fluid Flow - Work has commenced on building a detailed 2-D section for flow modelling.
- Task 1.7 Iterative Development of full Regional Geological Model – Work has commenced. Seismic data has been loaded and preliminary interpretation of the entire Utsira Sand has been completed.

Work carried out during the reporting period

<u>BGS</u>
The reprocessed CNST82RE survey has been loaded. Interpretation of the Utsira Sand transferred onto the reprocessed data and extended onto previously unavailable seismic lines. This completed the Greater Sleipner interpretation. Transferred reprocessed CNST82RE dataset to GEUS. Received additional Norwegian well information from GEUS. Contributed to paper presented at special session on CO2 at the EAGE meeting at Glasgow.

<u>GEUS</u>
Prepared abstracts and oral presentations for the special session on CO2 at the EAGE meeting at Glasgow.

Task 1.4. Characterise caprock (GEUS/SINTEF/BGS)

Work carried out during the reporting period

GEUS
Core material from a suitable cap rock analogue has been identified from the Ekofisk area in well 2/4-C-11. In collaboration with SINTEF a request for caprock samples have been sent to NPD, and we hope to receive a response in the near future.

SINTEF
Caprock core data from Ekofisk has been requested from NPD. A caprock sampling strategy has been devised for the ongoing Sleipner drilling programme.

BGS
Ways of characterising key sealing parameters from lithology and geophysical logs are being investigated and discussed with GEUS.

Problems and difficulties encountered

Sample data needs to be acquired as soon as possible and a coherent strategy for maximising information from the data needs to be devised quickly.

Task 1.6 Determine natural fluid flow (GEUS)

Work carried out during the reporting period

A NNW-SSE cross-section has been selected for the 2D basin modelling work. The cross-section is located in between the two seismic lines: CNST82-18BA and 82-19A. Log data from the wells N-7/1-1, N-15/12-3, N-15/9-4, N-15/9-3, N-15/5-3, N-15/3-1S, UK-9/23-1, N-24/9-4 and UK-9/13-3 are projected on to the cross-section. A preliminary interpretation of the lithology and porosity has been carried out on the basis of the gamma-ray and sonic logs acquired in the wells.

Task 1.7 Iterative development of full regional geological model (BGS/GEUS/SINTEF)

Work carried out during the reporting period

BGS

Loaded NNST84 and NVGT88 seismic surveys onto the workstation. All of the regional seismic data (~14000 line km) have been loaded. Preliminary interpretation of the Utsira Sand over the whole data set has been completed. Results from this interpretation summarised in paper submitted to GHGT-5 in Cairns.

GEUS

In order to characterise better the porosity of the Utsira Sand from geophysical log data, GEUS has calibrated the sonic log to the density log, to obtain consistent porosity estimates. This work is being discussed with BGS in order to set up a common approach to porosity determination using the sonic log alone (a density log in the Utsira Sand is only available from a few Norwegian wells).

Additional Norwegian well data have been received from Statoil and are currently being loaded on to the LandMark workstation. The CNST82RE seismic survey from GECO has been received from BGS and will be loaded in to the LandMark workstation.

References

Christensen, N.P. & Gerling, P. 2000. Assesment of the European potential for geological storage of CO2 from fossil fuel combustion. 62nd EAGE meeting, Glasgow, Paper B-18.

Gregersen, U.; Johannessen, P.N., Kirby, G.A., Chadwick, R.A. & Holloway, S. 2000. Regional study of the Neogene deposits in the southern Viking Graben area - a site for potential CO2 storage. 62nd EAGE meeting, Glasgow, Paper B-19.

Zweigel, P., Hamborg, M., Arts, R., Lothe, A., Sylta, O. & Tommeras, A. 2000. Prediction of migration of CO_2 injected into an underground depository: reservoir geology and migration modelling in the Sleipner Case (North Sea). 5th International Conference on Greenhouse Gas Control technologies, Cairns (Australia), August 2000.

Chadwick, R.A., Holloway, S., Kirby, G.A., Gregersen, U. & Johannessen, P.N. 2000. The Utsira Sand, Central North Sea – an assessment of its potential for regional CO_2 disposal. 5th International Conference on Greenhouse Gas Control technologies, Cairns (Australia), August 2000.

WP 2 – Reservoir Simulation lead by SINTEF and supported by TNO

Summary

Work has commenced in the following subtask:

- 2.2 Relative permeability and capillary pressure experiments
- 2.5 Numerical simulation of the present history of CO_2,
- 2.9 Escape of CO_2 from a fault or spill point

According to schedule these tasks has not yet started:

- 2.6 Numerical simulation of the long term fate of CO_2
- 2.7 Rayleigh convection

2.8 Transport properties of the boundaries of the Utsira formation
2.10 Limitations and improvements of reservoir simulators.

A presentation of results up to now for the GHGT-5 conference was prepared. This was financed by SINTEF.

Task 2.2 Relative permeability and capillary pressure experiments

A new experiment to measure relative permeability and capillary pressure in one experimental set up has been designed. The set-up involves use of X-ray computer tomography and high resolution differential pressure measurements.

Task 2.5 Numerical simulation of the present history of CO_2,

A 3D-model has been constructed of 2 km x 3 km area near the injection point based on geological information from well logs, seismic and core data. The image of the seismic reflectors obtained in September 1999 has been interpreted as CO_2 accumulations and this image was mimicked in the simulation by adjusting the permeability of five major shale layers that divides the sand. A paper for the CGHT-5 conference has been prepared.

Task 2.9 Escape of CO_2 from a fault or spill point

A 3D model has been constructed that features a fracture in the reservoir. The escape rate as function of the fracture properties has been modelled.

WP 3 – Geochemistry lead by BRGM and supported by BGS, GEUS and IFP

Summary

* Detailed workplan for the geochemistry work area (dated 11/04/2000).
* Lab experiments were revived after the time gap between SACS and SACS2.
* Presentation of the SACS and SACS2 activities in geochemistry at the Leeuwenhorst Workshop (4-5/04/2000) and SACS2 Technical Workshop at Stavanger (12-13/04/2000).
* Review of the paper written by Jonathan Pearce (BGS) for the Cairns GHGT-5 Conference (August 2000): 'How will reservoir and caprock react with injected CO_2 at Sleipner? Preliminary evidence from experimental investigations'.
* J.M. Pearce[1], I. Czernichowski-Lauriol[2], C.A. Rochelle[1], N. Springer[3], E. Brosse[4], B. Sanjuan[2], S. Lanini[2] and K. Bateman[1] ([1] BGS [2] BRGM [3] GEUS [4] IFP)
* International umbrella cooperation: Examination of the proposals submitted by LLNL and Battelle (USA)
LLNL: Reactive transport modelling of CO_2 storage within the Utsira formation at Sleipner.
Battelle: Hydrogeologic and Geochemical Modeling for Sleipner Aquifer Sequestration Project.

Task 3.2. Geochemical laboratory experiments

BGS

General comments

The gap between the SACS and SACS2 contracts resulted in a gap in the experimental programme. No new experiments were started in this period, though long term batch experiments were maintained. The experimental programme resumed with the start of SACS2. A key staff member was unavailable for several weeks due to paternity leave and the needs of EC proposal presentation. However, these should not affect the overall experimental programme in the long term.

Batch experiments

CO_2 solubility

A series of CO_2 solubility experiments have been completed using both de-ionised water and synthetic Utsira porewater. These will provide useful information on the efficacy of sampling techniques for the more important 'long term batch experiments' (see below), and should also provide extra data on the solubility of CO_2 under conditions relevant to injection conditions at Sleipner. Analysis of the solutions from the experiments is complete. These are currently undergoing interpretation, with a view to production of a brief report describing the experiments and the solubility results.

Long term batch experiments

These experiments are the main focus of the BGS geochemical experimental work. Several of the longest batch experiments were kept running between the SACS and SACS2 contracts. The effect of this will be to allow the experiments to be completed earlier (relative to the end of the contract) than expected. The longest experiments have been running for approximately 10 months, and the next set of these is due for sampling in the next few days. Further experiments, to run for intermediate timescales, will be started soon, as the necessary equipment becomes available.

Flow experiment

At the start of the SACS project it was hoped that there would be scope within the project budget to undertake a pair of long-term flow experiments on top of the batch experiments mentioned above. However, as the latter are the main focus of BGS activity most emphasis has had to be placed on these. Therefore, only one long-term flow experiment will be conducted. The experiment consists of a column of Utsira sand of total length 2.4 m. This is being flushed with synthetic Utsira porewater equilibrated with 10 MPa of CO_2 at 70 °C. Although the start of the experiment was delayed due to problems with our supplier of CO_2, it is now running. It is anticipated that this experiment will run for approximately 12 months. Periodic analyses of output fluid chemistry will be undertaken, with the mineralogy of the column determined at the end of the experiment.

GEUS

Two preserved plug samples taken from the frozen core have been run under the short to mid term dynamic flooding programme run at GEUS. Three experiments were carried out at reservoir temperature (37 °C) and lasted 14 days and 31 days respectively.

The first experiment was a blind run without CO_2 added to the formation brine. The following two experiments used CO_2 -saturated brine. The brine flow rate was set at two different values to look for changes in reaction rate between CO_2 -saturated brine and the minerals of the Utsira sand.

A number of brine fractions were collected and sent to BGS for analysis.

IFP

Preparation of the data for making ready to run the DIAPHORE-GAS version. The geochemical simulations done with this version will allow to represent equilibria between a gas phase (CO_2+CH_4) and the water phase that interacts with minerals.

WP 4 – Monitoring Well Asses. lead by Statoil and supported by IFP and SINTEF

According to plan this WP will be started in 2001

WP 5 – Geophysical Monitoring lead by TNO and supported by SINTEF, BGS, Statoil and BRGM

Summary
The general purpose of task 5 consists of:
- Qualitative interpretation of the geometrical extent of the “CO_2 bubble”
- Quantitative interpretation of the CO_2 saturation at different time steps
- Detection of leakage zones through the cap rock
- Mapping of the intra-Utsira shale layers
- Identification of the most likely migration pathways in the future
- Link/update the results with the reservoir simulations:
    - History matching (influence of the intra-Utsira shale layers)
    - Prediction of future CO_2 flow
- Investigate other geophysical monitoring techniques (gravity, micro-seismic monitoring, multi-component seismic data acquisition).

Important result: A worlds first!
A 3D seismic time-lapse survey over the injection site was shot in October 1999 over the same area as before any CO2 injection. The seismic contractor GECO has re-processed the initial survey and processed the time-lapse survey in “a time-lapse manner”. Quality control to verify the calibration of the base and time-lapse surveys has been performed by Statoil as well as the initial rough mapping of the CO_2. This produced the worlds first seismic image of injected CO2 ever. Earlier the very possibility to map the CO2 had been debated among specialists. Now it has been proven!

In the next section the progress is given for each subtask as defined in the original work plan.

Task 5.1 Sensitivity study determining whether gravity is likely to be useful to determine distribution of injected CO_2

Objective
Determine whether a high resolution 3D gravity survey over the disposal area would be able to detect the presence of injected CO_2. Produce a cost estimate for a reasonable data acquisition programme.

Status
The start of this subtask is planned in September 2000, when the 3-D seismic will be more fully processed and the present geometry of the gas cloud better understood.

Task 5.4 Twice run 3D seismic survey plus interpretation

Objective
- Acquire a first time lapse seismic monitoring survey in Phase 1 (October 1999)
- Acquire a second time lapse seismic monitoring survey in Phase 2 (2001)
- Process both surveys calibrated in a time-lapse manner
- Map the distribution of CO_2 within the Utsira Formation.

Status
A 3D seismic time-lapse survey over the injection site has been shot in October 1999. The seismic contractor GECO has re-processed the initial survey and processed the time-lapse survey in “a time-lapse manner”. Quality control to verify the calibration of the base and time-lapse surveys has been performed by Statoil as well as the initial rough mapping of the CO_2. The seismic data has been distributed among the project partners in April 2000.

The time-lapse seismic data is currently being interpreted in more detail by TNO-NITG in terms of locating the free CO_2 gas. To this end the interpretation of the intra-shale layers within the Utsira formation around the injection point is of utmost importance. Due to the amplitude effect of the CO_2, these thin layers are better detectable on the time-lapse seismic data. The CO_2 affects strongly the seismic velocities, so for mapping the intra-Utsira shale layers a detailed analysis of the velocity pull-down effect is being carried out.

Recently (in June) a multi-attribute analysis study has started at TNO-NITG to create property maps based on pattern recognition techniques.

Difficulties encountered
Initially a problem appeared to be present in the seismic data distributed. The amplitudes in the different cubes were not balanced. However, a correction factor has been provided (in the Segy trace headers) by Statoil.
The second problem concerns a small time shift between the (re-)processed 1999 surveys and the initially interpreted 1994 survey. This is currently investigated, since it has implications for calibration issues.

Task 5.5 and 5.7 AVO analysis and parameter maps of target area.

Objective
Subtask 5.7 is very closely related to subtask 5.5 and both will actually be treated as one. Assuming that amplitude anomalies are gas indicators, the CO_2 bubble will be localised in a more quantitative manner and a better understanding of the Utsira Formation and the Hordaland Shale will be obtained. This task could also give important information on the cap rock sealing. AVO analysis (and seismic inversion) should provide accurate data cubes of the target area of (combinations of) the seismic parameters V_p, V_s and the density.

Status
Amplitude vs. offset will be determined from gathers, and the intercept and gradient will be estimated. Furthermore, AVO inversion will be performed with an algorithm and tested on synthetic and real data. The scheme is layer based and provides estimates of the seismic parameters V_p, V_s and the density.
These parameters should then be transformed to parameter cubes of porosity and saturation using the results of rock physics analyses (for example including the Gassman Equation).
As part of the calibration process of the different seismic data sets, a good match should be realised between the seismic modelling results and the real seismic data. Forward seismic modelling based on the previous inversion results should provide a good match with the seismic data. Only then the seismic modelling can be used in a predictive way when for example saturation changes.

The resulting cubes or maps of the parameter inversion are important input to the reservoir simulation.

The background velocity trend coming from the seismic processing is required as well as pre-stack seismic data. As soon as these are available, task 5.5 can start.

Task 5.6 Determine the local seismic properties of the Utsira sand from well log analysis and investigate the feasibility of a multi-component survey.

Objective
- Make a detailed analysis of well log data in the area of the injection (ST98M11 3-D survey and surrounding).
- Sensitivity study/costing of 3-component surveys.

Status

The aim of the first part of this study is to aid seismic modelling and the planning of repeat seismic surveys over the injection point, by quantifying relevant physical properties of the Utsira Sand. The physical properties are to be derived from well logs. The study was confined to the area around the Sleipner fields.

25 wells from Norwegian Quadrants 15 and 16 were screened for the study. Of these only 12 wells were found to have enough logs over the Utsira Sand interval to determine the relevant physical properties. Further wells will be added to the data set when more UK sector well logs are downloaded from tape.

Results so far show, that the Utsira Sand is largely a clean sand, but it contains thin shale layers. These can be distinguished on the gamma ray log. It should be noted that no core samples of these shales exist and their lithology is inferred from cuttings descriptions and log analysis.

In the majority of wells the sand has gamma ray values less than 35 API units, whereas the shales have higher values. Therefore a gamma ray discriminator of 35 API units was used to discriminate between the sand and shale components.

Furthermore washouts appear to be common in the Utsira Sand. They can be identified on the caliper log. They result in poor quality log data (e.g. unrealistically high density porosity, unrealistically slow interval transit time). Intervals where the log quality is too poor for meaningful analysis were discarded by using a cutoff on the density porosity log, which corresponds to the likely maximum possible porosity for a moderately sorted fine grained sandstone such as the Utsira Sand. The choice of density porosity cutoff was important as it affects the apparent porosity by up to 2%. Choosing a lower cutoff lowers the apparent average porosity of the sand
All other factors being equal, the log readings are most likely to be accurate in the best gauge holes. The best gauge hole is 15/9-18, followed by 15/8-1. In both these wells the density porosity of the sand component is significantly lower than in all the other wells (35.8% and 35.6% respectively). Although there is no direct evidence, it was felt that the lower apparent porosity in these wells is more likely to be due to good hole conditions rather than the good hole conditions being due to the lower porosity. Consequently a density porosity cutoff of 40%, corresponding to the highest density porosity values in 15/9-18, was used in the analysis.

Results concerning densities, transit times, velocities and impedances are available as individual well reports (on a data point-by-data point basis), log plots, crossplots or maps. Further investigations to additional properties will be continued based on the data required for other subtasks.

The second part of task 5.6, namely the feasibility study on multi-component data, is based on results of the seismic interpretation and will therefore start in September 2000.

Task 5.8 Report evaluating cost, practicality and benefits of micro-seismic monitoring

Objective
- Evaluation of the costs, practicality and benefits to detect the distribution of CO_2 in the storage reservoir
- Feasibility study to estimate whether detectable micro-seismic events will occur

Status
The work has focussed mainly on gathering literature and assessing the state of the art of data acquisition and processing so far.

Technical meetings

So far the following technical meetings have been taken place or have been planned:
- Stavanger, 12-13 April 2000: Technical meeting discussing the workplans for SACS 2.
- Trondheim, August/September 2000: Technical meeting using the dedicated visionary room of Statoil, where the time-lapse seismic data is loaded including people from Geco-Prakla.
- Orleans, 26-27 September 2000: Technical meeting discussing the progress.

Technical dissemination

So far presentations have been given for:
- 4-5 April 2000, Geological Storage Workshop in Amsterdam
- 29 May – 2 June 2000, EAGE conference in Glasgow

- 6-11 August 2000, SEG conference in Calgary
- 13-16 August 2000, GHGT-5 conference in Cairns

with the following references specifically for task 5:

References

Arts, R.J., Brevik, I., Eiken, O., Sollie, R., Causse, E. and Meer, L.G.H. van der, 2000. Geophysical methods for monitoring marine aquifer CO2 storage – Sleipner experiences. 5th International Conference on Greenhouse Gas Control Technologies, Cairns (Australia), August 2000, accepted.

Brevik, I., Eiken, O., Arts, R.J., Lindeberg, E. and Causse, E., 2000: Expectations and results from seismic monitoring of CO2 injection into a marine acquifer. 62nd EAGE meeting, Glasgow, paper B-21.

Eiken, O., Brevik, I., Arts. R., Lindeberg, E., & Fagervik, K. 2000: Seismic monitoring of CO2 injected into a marine aquifer. SEG Calgary 2000 International conference and 70th Annual meeting, Calgary, accepted.

WP 6 – Reports&"Best-Practice." lead by Statoil and support by BGS, GEUS and SINTEF

Two sub-tasks: 6.1 Reporting and 6.2 "Best-Practice-Manual".
Task 6.1 Reporting produced this "Management Report" with elements collected from active institutes through Work Area Leader to Co-ordinator.

Task 6.2 "Best-Practice-Manual" will, according to plan, be started in 2001.

WP 7 – Thermodynamic and petro-acoustic lab lead by IFP

Objectives
To investigate the effects that mixtures of CO_2, methane and brine have on the seismic in order to contribute towards fruitful analysis of the seismic.

Status
This short period of laboratory work was devoted to the preparation of petro-acoustic experiments based upon high accuracy P and S velocity measurements in a rock sample when varying the saturating liquid compressibility. The goal is to check the possibility of deriving a reliable rock "dry" modulus. Using Ethanol-Ethylene Glycol mixtures we are able to vary the liquid bulk modulus between 1 and 3 GPa.

WP 8 – Base Interpretation lead by Geco

Summary
The processing sequence for '94 and '99 has focused on maximising the repeatability of the time-lapse seismic and the best match for the two surveys in the gas-injection zone. The conclusion from the characterisation exercise of the data is that the repeatability between the surveys is good, but compensations for the velocity-changes in the gas zone will increase our understanding of the time-lapse data. As little or no compensation of the differing velocities has been undertaken in the processing, it becomes possible to estimate intra-Utsira seismic velocities by using the geometric interpretations as input. Preliminary results of this have been presented in this report.

Task 8.1 Characterisation of the time-lapse seismic data

Time-lapse seismic data has the potential of identifying and pinpointing subtle changes that have occurred in e.g. a hydrocarbon reservoir during the time interval in question, at a distance of several kilometres underneath the seabed or earth surface. However, care must be taken in the analysis of the seismic data, as changes in the response may originate from several different sources. Typical reservoir parameters that will induce changes in the seismic response are changes in the fluid and gas saturation levels, changes in rock porosity, as well as changes in reservoir pressure and temperature.

The changes in the seismic response may also be related to changes in the acquisition parameters. Examples of such parameters are the number of streamers, the spatial positioning of the hydrophones or geophones, the cable lengths, the source type and the ability of these sources to repeat the wavelets that are transmitted down the sub-surface. Due to a particularly hostile environment, marine seismic surveys are to a large extent subject to such changes in the acquisition parameters: Ocean currents cause feathering in the streamers, waves will cause variable time shifts and ghost effects, and the tidal effect will cause slowly varying time shifts between the two surveys.

It is the aim to minimise the effects of the changes in acquisition parameters, in order to relate changes in the seismic response to the changes in reservoir parameters. Hence, the seismic processing of time-lapse data aims at maximising the repeatability of the different surveys, by using a range of different signal processing techniques. In order to validate the repeatability, and to improve our understanding of the available seismic data, an extensive characterisation of the data is currently undertaken, and some of the preliminary results will be presented in the following sections.

Task 8.2. Relative time shift analysis

The seismic signal should not change above the Utsira Formation unless the gas has migrated from the Utsira Formation to these areas. A good measure of the repeatability of the data sets will hence be obtained through an analysis of the seismic signal in the overburden.

In order to analyse the repeatability of the two seismic surveys, a set of reflectors in the overburden was interpreted on both seismic surveys. Information of interpretation methods and software will be given in Section 0.

Figure 8.1 shows the time differences for some reflectors both over, inside and below the Utsira Formation. On the time difference along the seabed, the acquisition footprint is clearly visible. However, this feature is gradually reduced further down in the section, and about 200 ms above the Utsira Formation it has almost vanished. This is due to a time shift compensation that was undertaken in the processing of the seismic data. The compensation was based on swath dependent time shifts in the range between 800 and 1200 ms.

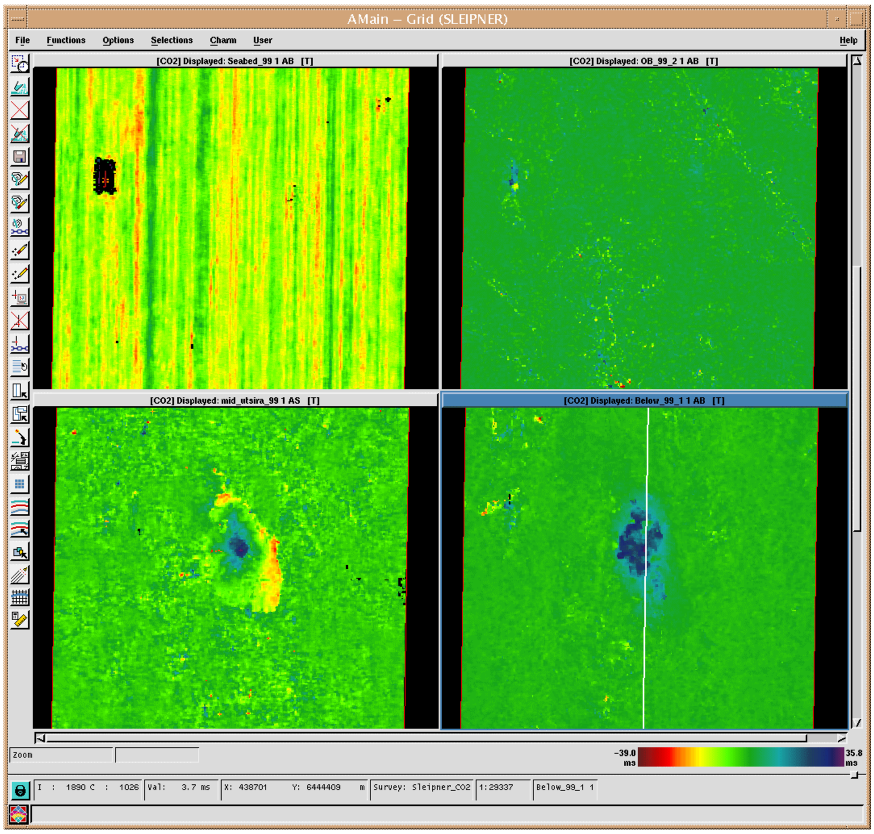

Figure 8.1. Time difference for reflectors between the 99 survey and the 94 survey. *Upper left corner*: Seabed. *Upper right corner*: Reflector 200 ms above Top Utsira. *Lower left corner*: In the middle of the Utsira Formation. *Lower right corner*: Reflector 200ms below Base Utsira.

In the middle of the Utsira Formation, large time differences between the two surveys may be observed around the injection point. The time shifts are both positive and negative, in the range of +/-25ms. A pull-down effect is observed at the base of the Utsira Formation, proving that the seismic wave field experiences a substantial velocity reduction when travelling through the CO_2 gas cloud. At the edges of the cloud, pull-up effects are observed, introducing a parabola-like reflector geometry. The reason for the pull-up are most likely due to effects introduced by the pre-stack time migration that was performed in the prior processing sequence of the seismic data. This effect is illustrated in Figure 8.2.

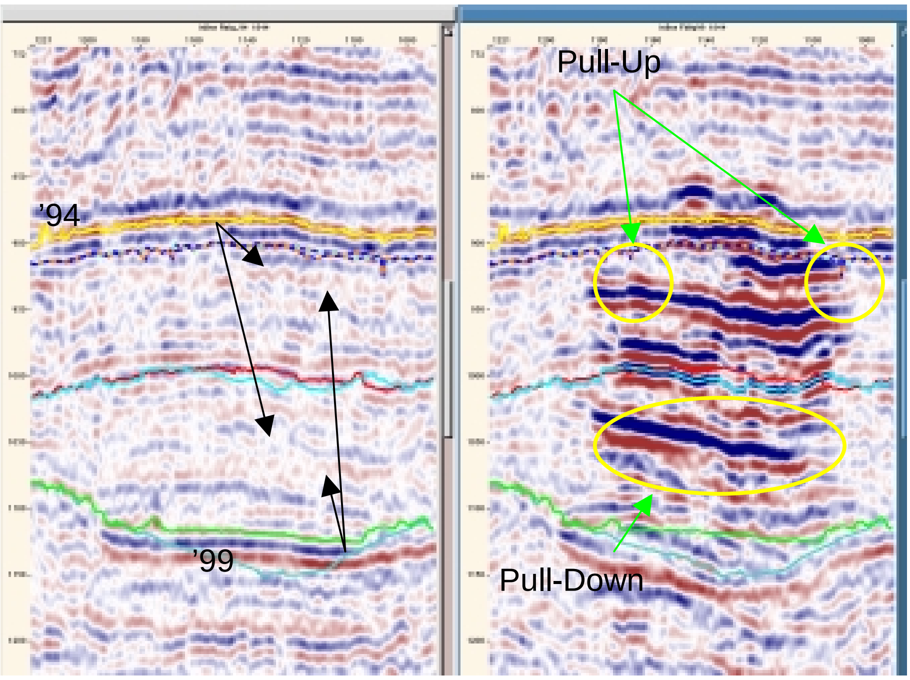

Figure 8.2. Illustration of "pull-up" and "pull-down" effects in gas cloud. The '94 data is shown to the left, whereas the '99 data is shown to the right.

Some differences have been observed between the two surveys that may be related to small differences in processing between them. This is exemplified in Figure 8.3, where vertical striping effects have been observed on the '94 seismic data. This "noise" results in less continuous reflectors, and makes the interpretation less accurate. Compensation for this could be done by post-processing the '94 seismic data with filters that enhance lateral continuity.

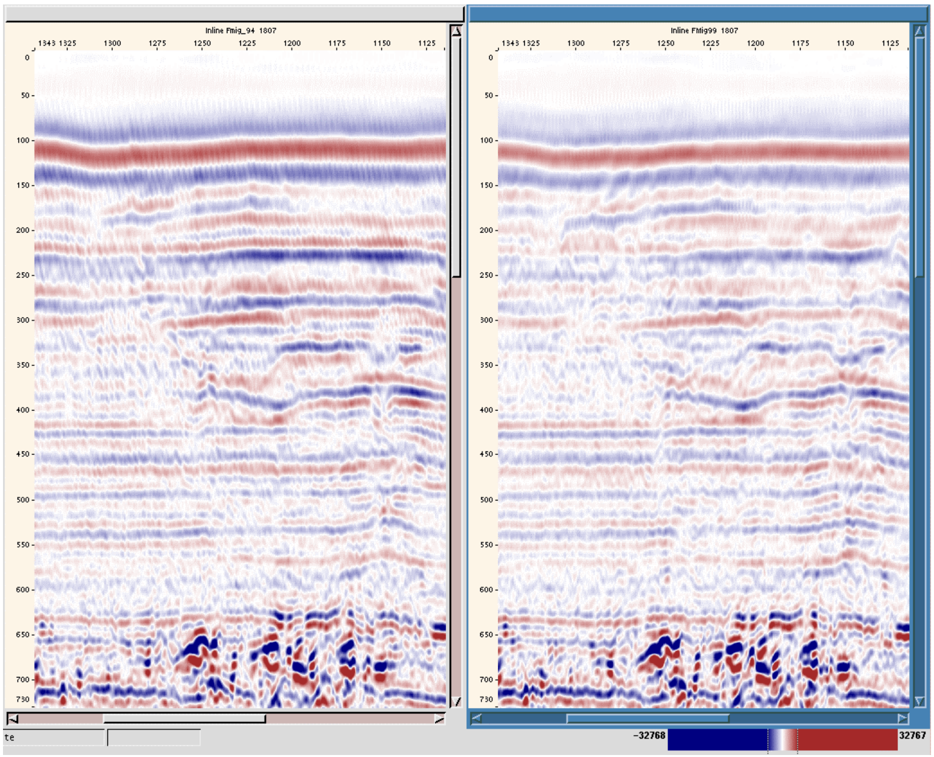

Figure 8.3. *Left panel*: 94 final migrated seismic from seabed with vertical striping. *Right panel*: 99 final migrated seismic.

WP 9 – Time Lapse 1 Interpret. lead by Geco

Task 9.1 Seismic Data Interpretation

In order to map the internal layering of the Utsira Formation and in order to obtain a detailed outline of the injected gas, a high quality signal-consistent interpretation had to be extracted. Automatic interpretation tools like ASAP in Charisma or manually interpretations have been used to extract the geometry of the first seismic survey (1994). Then a cross-correlation based method called 'Time Shift Search (TSS)' has been used in order to find the matching geometry of the second seismic survey (1999).

Regional interpretation of the Utsira Formation
The seismic interpretation of the Utsira Formation is mainly based on the work described in [3]. In the interpretation, the Utsira Formation was divided in two units, i.e. upper and lower Utsira, separated by the mid Utsira unconformity. The complexity in the Utsira Formation, with low-amplitude discontinuous reflection patterns, makes it difficult to subdivide the Formation into regionally correlative units. It has been possible to interpret some reflection events over the entire survey in the upper Utsira, while it is still a challenge to map seismic events of regional extent within the lower Utsira.

Seismic interpretation was undertaken on the '94 and '99 survey on the most continuous and correlative reflectors inside the Utsira Formation. The interpretation was undertaken on the '94 survey, after which cross-correlation was used in order to match the interpretation to the '99 survey. Inside the gas-affected area the matching will not work properly due to the velocity-anomaly in this area. Hence, manual interpretation was undertaken in this zone.

With reference to Figure 9.1, the following horizons with regional extent were interpreted:

- *Top Utsira* characterised as strong positive seismic reflection events over the whole CO_2-survey.
- *Upper Utsira 1*, which is the first maximum correlative event below top Utsira. This reflector is parallel to the top Utsira in most of the area and has a semi-transparent reflection pattern.
- *Upper Utsira 2* is a positive seismic event approximately 50ms below the top Utsira reflector. It has a transparent to semi-transparent reflection configuration.
- *The Mid Utsira* unconformity has been interpreted on a negative phased, continuous reflection event.
- *Base Utsira* is the very strong reflection event that has been disrupted by possible clay diapirism.

The interpretations for the two surveys will be used in the time-lapse mapping of the gas-affected Utsira Formation. The interpretations are illustrated in Figure 9.1. They have also been used as reference when producing a seismic difference cube, as a relative time scaling is required between the pre- and post-injection data in order to obtain event matching in time in the zone affected by the gas.

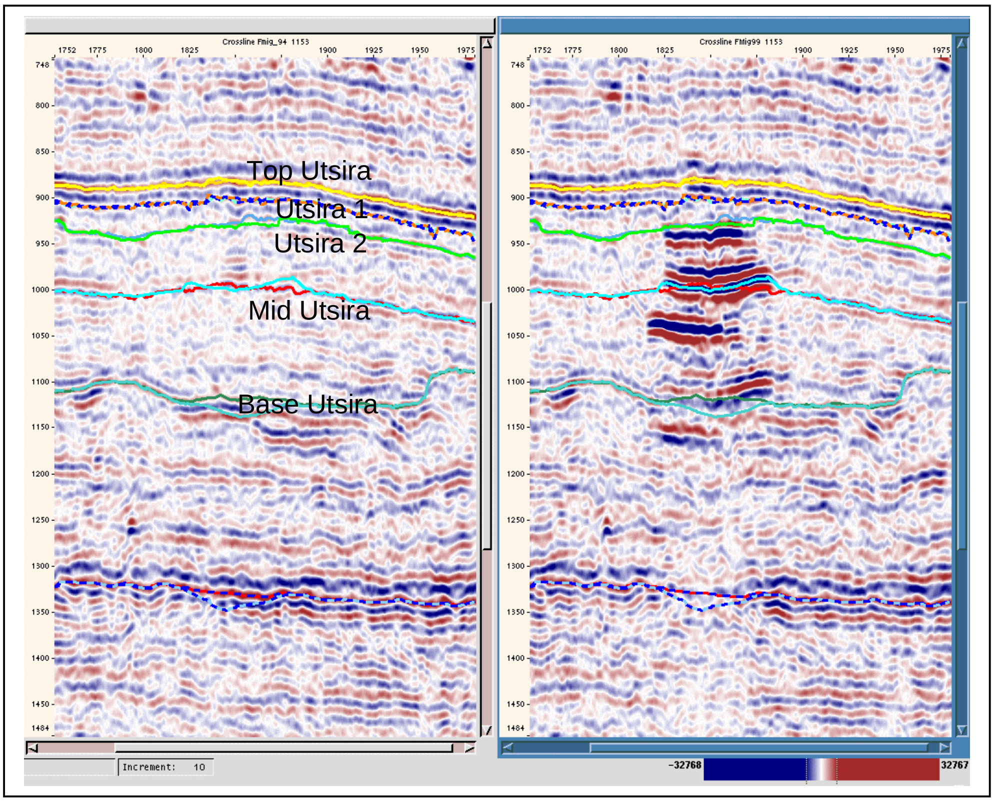

Figure 9.1. Interpretation in the 94 seismic cube (to the left) and the 99 seismic cube (to the right) highlighting the velocity-"pull-down" that has occurred in the gas-affected area.

Task 9.2 Velocity Analysis

It is of considerable interest to estimate the seismic velocities within the Utsira Formation, as there is a great potential for relating these velocities directly to the post-injection CO_2 saturation levels. Modelling in this respect has previously been undertaken in the SACS consortium, and results of this were presented in [1] and [2]. The model is represented in Figure 9.2. During the course of this project, velocities will be aimed extracted at the pre-stack level in order to obtain cell based velocity estimates. However, initial experiments have been run at the post-stack level, where velocities over volumes have been averaged and projected onto surfaces.

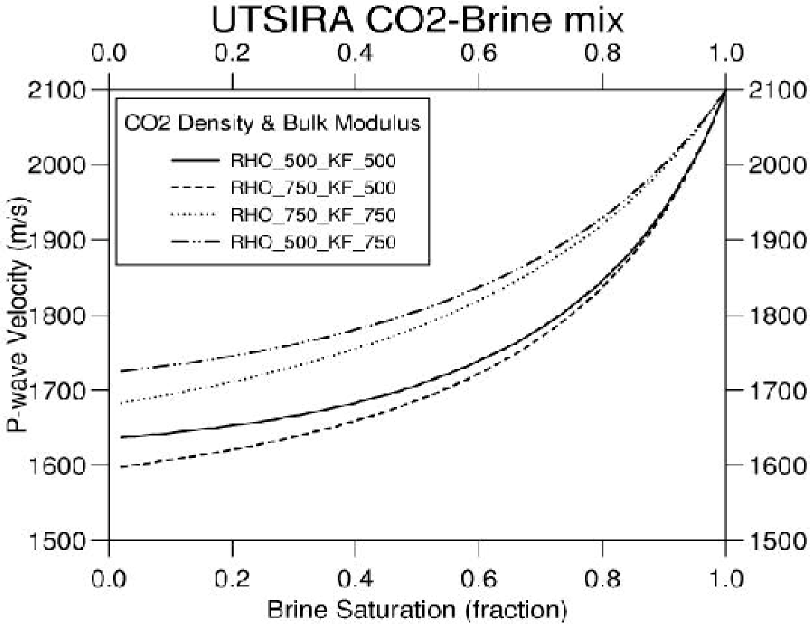

Figure 9.2. Relationship between brine saturation (CO_2 mix) and P-wave velocity, as given in [1] and [2].

The velocity of the CO_2 saturated rock between the top Utsira and the middle of the Utsira Formation has been estimated by considering the geometric interpretations that were treated in Section 0. We denote the pre-injection travel time between the top and mid Utsira t_0, and the post-injection travel time t_1. The relationship between these two variables is such that $t_1 = t_0 + \Delta t$, where Δt is the excess travel time due to lower velocities in the CO_2 cloud. We then use the models obtained in [1] and [2] in order to find the initial velocity in the Utsira Formation, assuming 100% water saturation. As is clear from the curve in Figure 9.2, the fully water saturated Utsira Formation should have a velocity of 2100 m/s. We denote this velocity v_0, and assume that this is uniform throughout Utsira. We denote the post-injection velocity in the Utsira Formation v_1, and assume that also this is uniform in the depth interval in question. We denote this interval, i.e. the thickness between the top and mid Utsira L. The ratio between v_1 and v_0 hence becomes:

$$\frac{v_1}{v_0} = \frac{\frac{L}{t_0 + \Delta t}}{\frac{L}{t_0}} = \frac{t_0}{t_0 + \Delta t} = \frac{t_0}{t_1}, \qquad \text{Equation 0.1}$$

which of course implies that v_1 may be estimated by

$$v_1 = v_0 \cdot \frac{t_0}{t_1}, \qquad \text{Equation 0.2}$$

This simple algorithm was applied on the Utsira Formation, resulting in the velocity grid depicted in Figure 9.3. As is noticeable, the pull-up effect at the edges of the CO_2 cloud results in higher velocities than in the original survey, i.e. more than 2100 m/s, whereas the pull-down effect results in lower velocities.

These results may thence be directly related to the CO_2 and water saturation level, and a variety of uses may be found for such saturation and velocity grids. It is hence of importance to undertake interpretations of several intra-Utsira reflectors, so that these post-stack velocity grids may be further refined. However, the method relies on high quality interpretation, and processing artefacts will introduce errors. Hence, a velocity analysis of the pre-stack data is necessary.

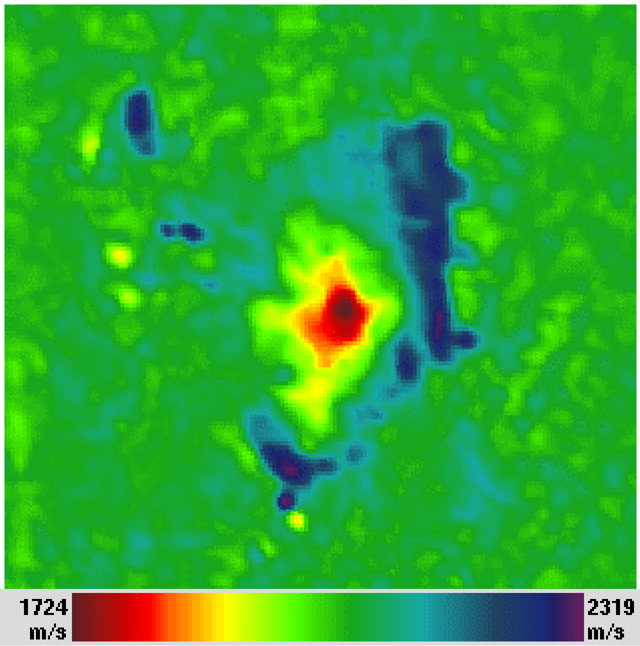

Figure 9.3. Illustration of velocity grid extracted for the '99 survey.

References

[1] Ivar Brevik, Ola Eiken, Rob Arts, Erik Lindeberg and Emmanuel Causse, '*Expectations and Results from Seismic Monitoring of CO2 Injection into a Marine Aquifer*', EAGE 62nd Conference and Technical Exhibition, Glasgow, Scotland, 29 May - 2 June 2000, article B-21.

[2] Ola Eiken, Ivar Brevik, Rob Arts, Erik Lindeberg, Kjetil Fagervik, '*Seismic Monitoring of CO2 injected into a marine aquifer*', SEG 2000, Calgary, Canada, August 2000.

[3] Ulrik Gregersen, Olaf Michelsen and Jan C. Sørensen, '*Stratigraphy and facies distribution of the Utsira Formation and Pliocene sequences in the northern North Sea*', Marine and Petroleum Geology, Vol. 14, No. 7/8, pp. 893-914, 1997.

WP 10 – Time Lapse 2 Interpret. lead by Geco

This WP will start in year 2001.

WP 11 – Synchronisation Res.Sim. lead by Geco

WP 11 will start in 4. Quarter 2000.

WP 12 – Steering Committee lead by Statoil

Steering Committee Meeting ("Kick-off") was held in Stavanger 13. April 2000.
Next Steering Committee Meeting will be held in Orleans 27. September 2000.

In between the SC has by E-mail discussed and decided topics like:
Procedures for accepting papers at conferences etc, Guidelines for international co-operation (involving transfer of data belonging to the SACS partners), and more.

1.3 Comparison of planned and actual work

Since the project commenced by 1 April and reporting period is only 3 months, any comparison is not meaningful yet.

1.4 Planned activities for next period

Technical Session and Steering Committee is planned at BRGM, Orleans 26.- 27. September 00.
August was basically “occupied” by the presentations at the international conferences; at the EAGE, Glasgow, at SEG, Calgary and 7 at the “5.Greenhouse Gas Technology”, Cairns.

WP 1 - Geology
Task 1.3 complete.
Task 1.4 Devise and implement strategy for regional characterisation of the caprock from available cuttings data and well log analysis. Analyse Sleipner and Ekofisk material if/when it becomes available.
Task 1.6. Interpret the reprocessed CNST82RE seismic data to refine the cross-section and extend it NNW into the UK sector. Interpretation of log data from additional and relevant UK wells (UK-9/17-1A, UK-9/12-3 and may be a few more depending on data availability). Carry out 2-D basin modelling on cross-section.
Task 1.7. BGS to transfer Utsira Sand interpretation to GEUS. BGS and GEUS will finalise Utsira Sand interpretation. Incorporate detailed information around Sleipner from SINTEF. Identify need for infill seismic data and seek to obtain these data. Evaluate and map small faults and ‘bright spots’ around Sleipner (SINTEF) and more regionally (BGS/GEUS). Start to reconcile formation tops in well database with seismic interpretation (BGS/GEUS).

2. Management and Co-ordination aspects

2.1 TECHNICAL MEETINGS

The following technical meetings have taken place or are planned:
- Stavanger, 12-13 April 2000: Technical meeting discussing the workplans for SACS2.
- Orleans, 26-27 September 2000: Technical meeting discussing the progress.

2.2 TECHNICAL DISSEMINATION

Presentations have been given/planned for:
- 4-5 April 2000, Geological Storage Workshop in Amsterdam
- 29 May – 2 June 2000, EAGE conference in Glasgow
- 13-16 August 2000, GHGT-5 conference in Cairns