GEOPHYSICAL METHODS FOR MONITORING MARINE AQUIFER CO_2 STORAGE – SLEIPNER EXPERIENCES

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INTRODUCTION

Since October 1996, Statoil and its Sleipner Partners have injected CO_2 into a saline aquifer at a depth of approximately 900 m, with an injection rate of 1 million tons per year. The aquifer consists of the Utsira Sands with thicknesses around 200 m near the injection site, sealed by thick shales (Fig. 1). A multi-institutional research project SACS (Saline Aquifer CO_2 Storage) was formed to predict and monitor the migration of the injected CO_2. Alternative ways of monitoring the injected CO_2 were discussed initially. A repeat surface 3D seismic survey was found to be most favourable both from a technical and economic point of view.

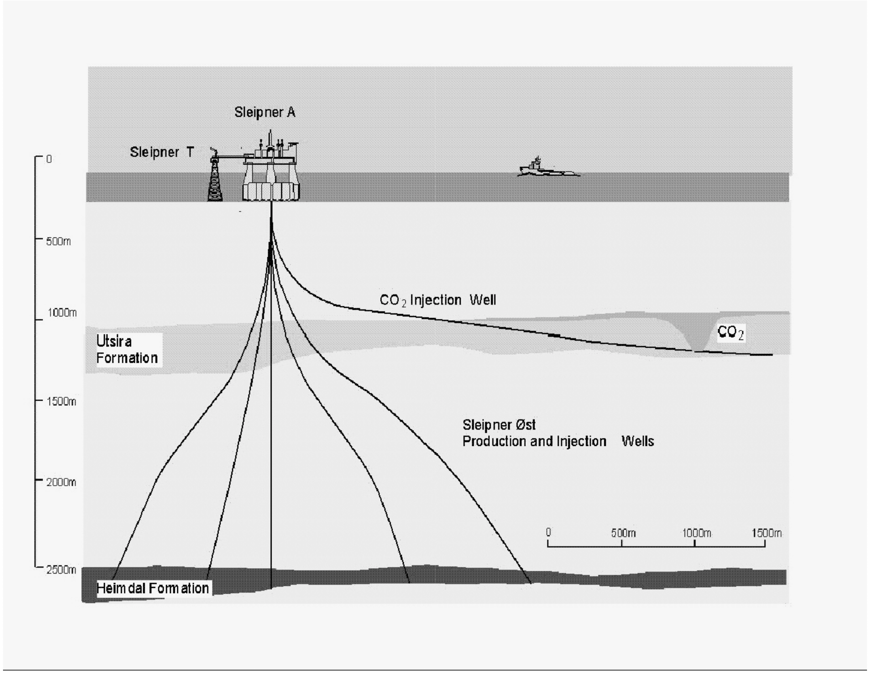

Figure 1: Cross section through the injection well.

In October 1999 a time-lapse survey over the injection area was acquired and currently the seismic data are being interpreted both qualitatively and quantitatively in terms of CO_2 migration and saturation. The 3D time-lapse survey covers an area of approximately 4 by 7 km. An interpretation loop composed of flow simulation, property modelling (including the water/ CO_2 mix and the rock properties) and seismic modelling is envisaged (van der Meer et al., 2000).

GEOLOGICAL BACKGROUND

The existing 3D seismic survey over the Sleipner field provided important insights into the local geology of the area immediately surrounding the injection site (Holloway et al., 2000). Four key reflectors have been interpreted on the basis of well logs, i.e. Top Pliocene Prograding unit, Intra-Pliocene Prograding Unit, Top Utsira Sand and Base Utsira Sand (Fig. 2). The same reflectors have been picked in a more regional stratigraphic study of the reservoir.

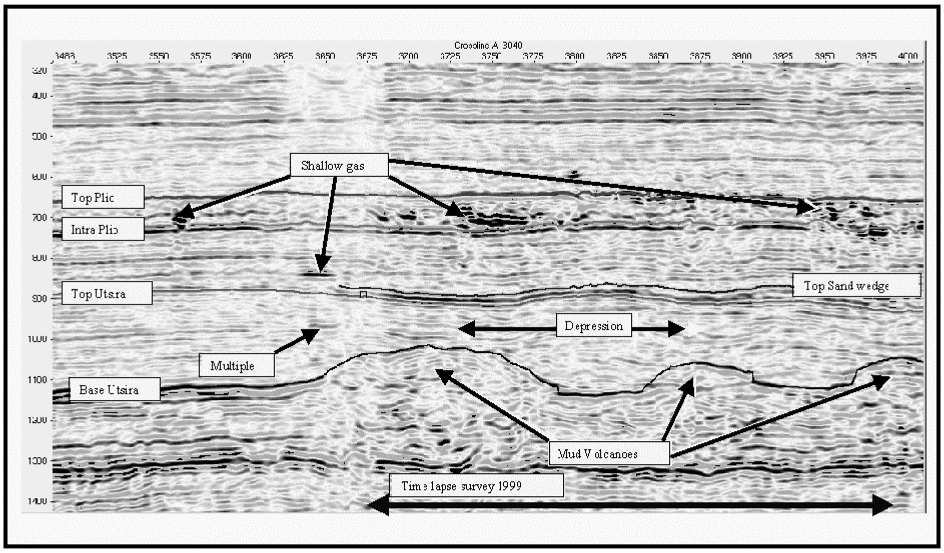

Figure 2: Interpreted seismic line of the 1994 base survey.

The Utsira Sand is of a Miocene-Early Pliocene age with a thickness of about 200 m. Mounds were mapped at the base of the Utsira Sand and have been interpreted as being caused by mud volcanism and mud diapirism, which was active during deposition of the lower part of the Utsira Sand. The presence of these shale mounds induced compaction and subsidence anomalies, which led to depressions of the Utsira Sand and overlying units above the mud volcanoes. This can be observed in Fig. 3. These depressions constitute local modifications of the general southward dip of the top of the Utsira Sand, including local domal and anticlinal structures, which probably act as traps and/or channels during CO_2 flow (Holloway et al., 2000 or Arts et al., 2000).

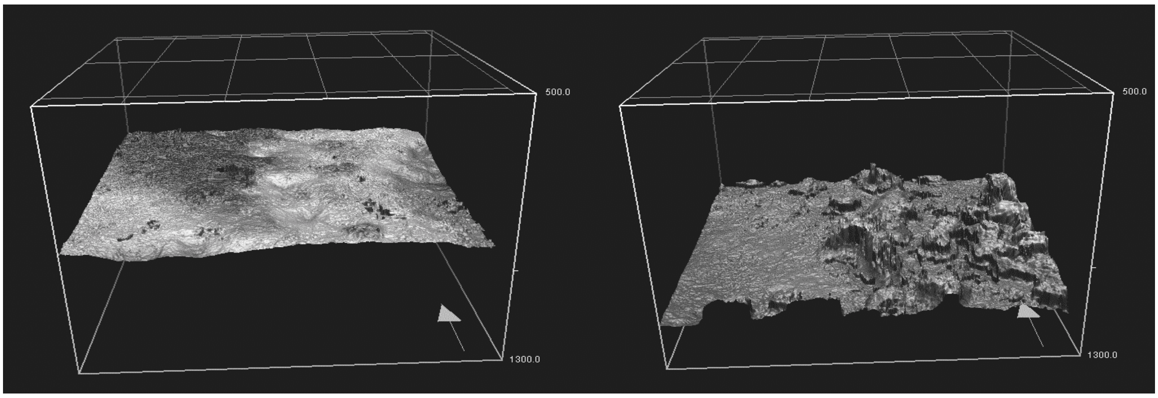

Figure 3: 3D view of the top Utsira (left) and base Utsira (right) Sands

Within the Utsira Sand, several (up to 14) thin (<1m) shale layers have been identified. These intra-Utsira shale layers influence migration of CO_2 near the injection site and must be mapped accurately to predict "short-term" (probably up to 5 years) migration.

The thick Pliocene shales of the cap rock can be subdivided into 2 units. The lower one, directly overlying the Utsira Sand includes at its base a shale drape that can be distinguished on a regional scale (Holloway et al., 2000).

MONITORING TECHNIQUES CONSIDERED

Alternative ways of monitoring the injected CO_2 were discussed initially, such as an observation well or repeat electrical, gravity and seismic observations. Seismic surface 2D or 3D surveying as well as borehole monitoring (active and passive) was considered. A repeat surface 3D seismic survey was considered most likely to produce results both from a technical and economic point of view. The number of recent time-lapse seismic success stories acquired with conventional streamers strengthened the SACS partners in their conviction to use this technique.

The main reasons not to drill a monitoring well as yet were the high cost, the lack of information about the area and the risk of puncturing a CO_2-containing structure. Other geophysical methods such as micro-seismic monitoring and gravity surveying are still subject to more detailed feasibility studies for possible future application.

SEISMIC FEASIBILITY STUDY

The feasibility of time-lapse seismic measurements was shown by modelling the expected seismic response before and after injection of gas (Lindeberg et al., 1999). In the Utsira Sand, the CO_2 has a high compressibility when the temperature is just above the critical temperature (Baklid et al., 1996). Because the rock matrix in the Utsira Sand is weak, the compressional velocity is also unusually sensitive to the compressibility of the fluid. Therefore, the presence of gas induces a dramatic drop in the compressional wave velocity even for moderate gas saturations, leading to a clear change in seismic response. This is expressed in a change in amplitude of the reflection and in a change in traveltime through the CO_2 accumulations ("velocity pushdown effect").

Two main types of interfaces have been evaluated. The first consists of a CO_2 accumulation just below the sealing Pliocene shales. The second corresponds to small CO_2

accumulations under the thin, (up to 1-m-thick), intra-Utsira shale layers. In both cases modelling predicted a clear change in seismic response. Qualitatively this has been corroborated by the initial interpretation of the time-lapse seismic data (Brevik et al., 2000 or Eiken et al., 2000).

AVO (Amplitude versus Offset) effects induced by the CO_2 are expected to be small. This will be verified on the seismic data.

ACQUISITION AND PROCESSING PARAMETERS

The first 3D time-lapse seismic survey was acquired in October 1999, three years after injection started. Vital parameters, such as shooting direction, nominal line spacing and tow depths were kept the same as in the base survey.

Table 1: Main acquisition and processing parameters

Parameters	1994	1999
Shooting direction	N-S	N-S
Shotpoint interval (flip-flop)	18.75 m	12.5
No. of airguns	30	24
Total airgun volume	3400 in^3	3542 in^3
No. of streamers	5	4
Crossline nominal spacing	25 m	25 m
Source towing depth	6 m	6 m
Streamer towing depth	8 m	8 m
Residual swath-consistent time shifts		Yes
Residual global spectral matching		Yes
Stack fold normalisation	Sqrt(40)	Sqrt(60)

Table 1 shows the main acquisition and processing parameters. Only the shotpoint interval was changed from 18.75 m to 12.5 m to get a higher fold. However, having seen the data, we believe that a careful repeat of all acquisition parameters is not critical in this spectacular monitoring task. In the simultaneous processing of both vintages, care was taken to equalise the wavelets, timing and gain of the surveys, which is important for a high-quality result. Further processing was kept identical, except for stacking and migration velocities applied in the region, in which CO_2 accumulates.

INTERPRETATION

At several levels within the Utsira Sand, a large increase in reflectivity can be observed on the time-lapse seismic data of 1999 (Fig. 4). Those changes are restricted to a semi-circular area of less than 1-km radius with a slightly elongated shape in a N-S direction. Different amplitudes are up to three times as large as the initial reflections from this area. Below the CO_2 bubble, a velocity pushdown can be observed. The saturation pattern seems heterogeneous, making the presence of gas flow barriers in the form of thin shale layers likely.

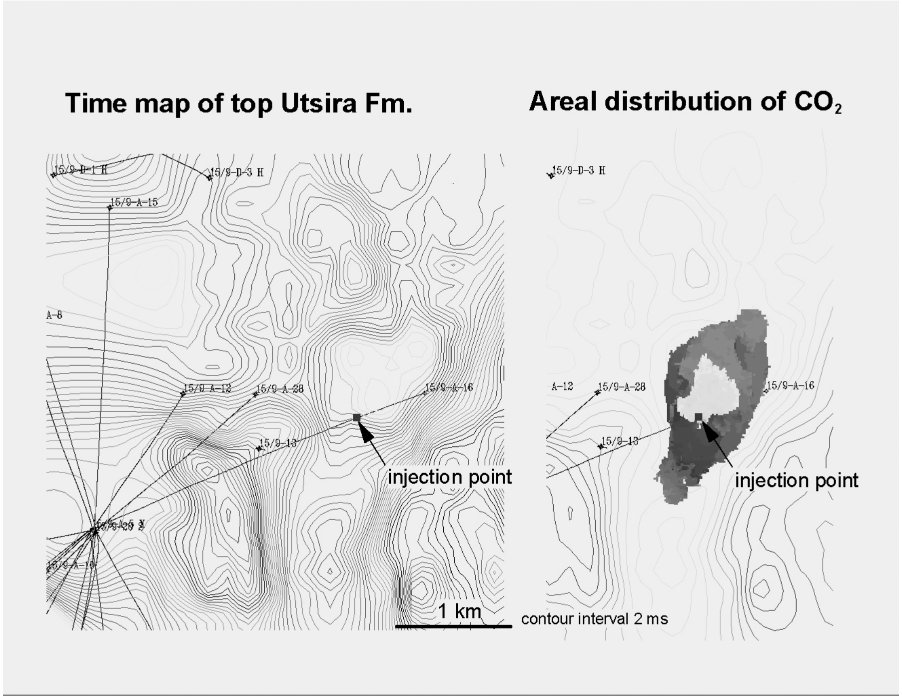

Figure 4: Interpretation of the time-lapse seismic data in the CO_2 bubble.

The exact depth and extent of the thin intra-Utsira shale layers is very important for short-term reservoir simulation covering approximately the first five years of the project. After that period migration will probably be controlled by the topography of the top seal and horizontal permeability (Zweigel et al., 2000).

A detailed velocity analysis is carried out over the CO_2 bubble to compensate for the velocity pushdown effect.

DISCUSSION AND CONCLUSIONS

Time-lapse seismic surveying appears to be a suitable geophysical technique for monitoring CO_2 injection into a saline aquifer. The effects of the CO_2 on the seismic data are large both in amplitudes as in time delays observed (velocity pushdown effect).

The thin intra-Utsira shale layers affect short-term CO_2 migration in the vicinity of the injection area. In the long term (a period of five years or more), migration is expected to be controlled mainly by the topography of the top seal and horizontal permeability.

In addition to straightforward mapping of changes in the time-lapse seismic data, quantitative approaches to mapping the free CO_2 gas saturation are currently under investigation. Because of the shallow depth, the favourable rock properties and the large acoustic contrasts this seems feasible. An interpretation loop comprising flow simulation, property modelling (including the water/ CO_2 mix and the rock properties) and seismic modelling is envisaged.

ACKNOWLEDGEMENTS

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