RECENT TIME-LAPSE SEISMIC DATA SHOW NO INDICATION OF LEAKAGE AT THE SLEIPNER CO_2-INJECTION SITE

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ABSTRACT

Injection of CO_2 into the Utsira Sand, a saline aquifer at the Sleipner site in the North Sea, has been in progress for more than seven years, with an annual rate of approximately one million tonnes. This project is considered as the first industrial-scale, environmentally driven CO_2 injection project in the world. In consequence, a European research project (initially called SACS succeeded by the ongoing CO2STORE) has been organized around it, with special focus on monitoring and simulation. To that end, four seismic surveys have so far been acquired, one prior to injection, and three afterwards in 1999, 2001 and 2002. In this paper results from the 2002 survey will be presented for the first time and compared to findings from the previous surveys. The major conclusion is that there are still no indications of CO_2 leakage to levels shallower than the Utsira Sand.

INTRODUCTION

At the time of writing, more than six million tonnes of CO_2 have been injected in the Utsira Sand at Sleipner (Figure 1) over a period of more than seven years. The Utsira Sand is a highly porous (35 to 40%) weakly cemented sandstone at a depth of about 800 m with a thickness of about 200 m around the injection site. The overburden comprises a predominantly mudstone-siltstone sequence up to the seabed with a direct seal of more than 200 m of silty mudstone directly above the reservoir. Within the reservoir itself, thin mudstone layers in the order of one metre thick have been identified. These layers slow down the upward migration of the CO_2. Several papers [1 to 5] contain more detailed reservoir descriptions.

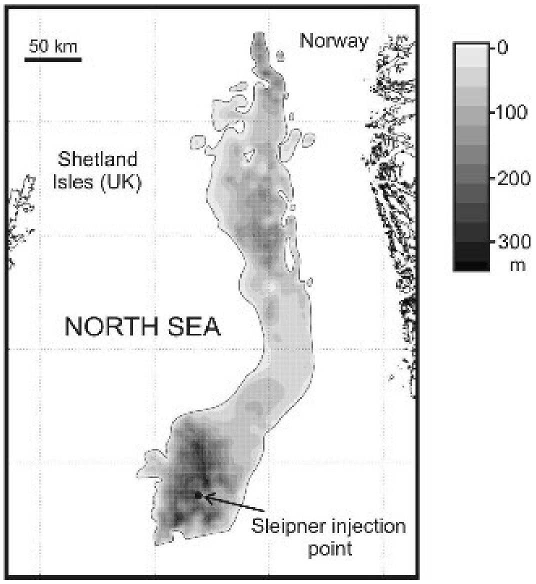

Figure 1: Location map of the Utsira Sand reservoir and the CO_2 injection point.

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The migration of CO_2 in the reservoir has been monitored with time-lapse seismic surveys [6 to 8]. The first time-lapse seismic survey was shot in 1999 with 2.35 million tonnes of CO_2 injected, the second in 2001 with 4.26 million tonnes of CO_2 injected, and the most recent in 2002 with 4.97 million tonnes of CO_2 injected. Comparison of the different time-lapse seismic surveys shows a large consistency with respect to the identified CO_2 accumulations. The fact that the time interval between the last two seismic surveys has been only eight months provides the opportunity to investigate the effect of a relatively small additional amount of CO_2 on the seismic amplitudes and on the observed pushdown. Furthermore, detailed analysis of the pushdown observed on the different time-lapse seismic datasets allows better constraints to be placed on the rock-physics model used to link CO_2 saturations to seismic velocities.

In conjunction with the 2002 seismic survey, a gravity survey was also acquired, with a repeat survey planned in 2005. It is hoped that the gravity data will place additional constraints on the seismic analysis, in particular by providing an independent estimate of in situ CO_2 density, a key parameter in quantitative modelling. From the results of the first gravity survey, it is hoped that changes as small as 5 μGal will be detectable.

INTERPRETATION OF THE SEISMIC DATA

The most important interpretive conclusion of the 2002 time-lapse seismic survey is that no indications of upward migration (or leakage) above the top Utsira have been observed. Figure 2 shows examples of difference sections between, respectively, the time-lapse surveys of 2002 and 1994, and of 2002 and 2001.

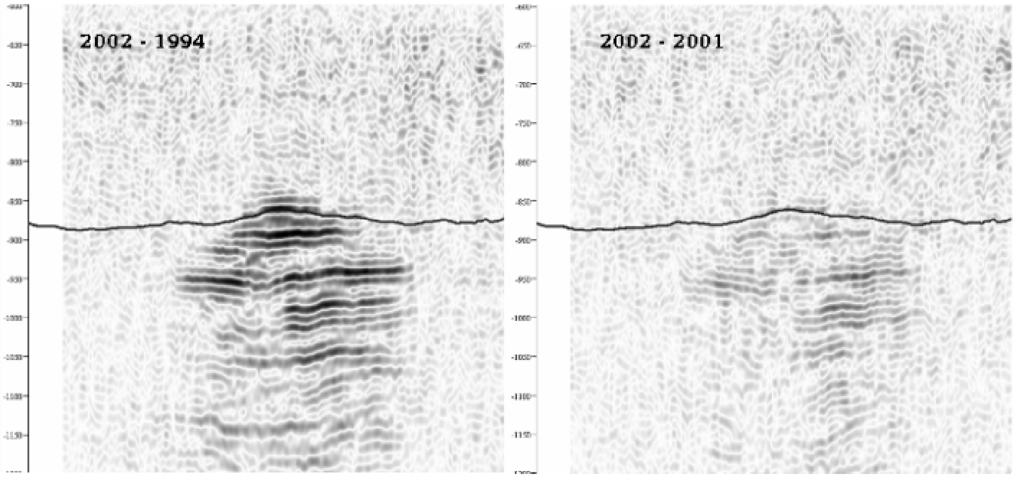

Figure 2: Inline from the 2002 minus 1994 seismic difference data (left) and the 2002 minus 2001 seismic difference data (right). The bold horizon indicates the top of the Utsira Sand reservoir as interpreted on the 1994 baseline seismic data on the maximum trough of the signal (timescale in milliseconds).

The effect of the CO_2 is clearly visible on the 2002-1994 difference data (Figure 2a). The presence of such amplitude anomalies above the top of the reservoir could indicate leakage to shallower strata, but no indications of amplitudes significantly higher than the background noise level are observed. Note that the high amplitudes in the centre just above the top of the reservoir are a sidelobe of the seismic signal and are not indicative of leakage. A more thorough explanation can be found in [9]. Figure 2b shows the 2002-2001 difference data (plotted at the same scale as Figure 2a). The effect of the CO_2 is again visible, but much weaker, the relatively small additional amount of CO_2 producing changes mostly in the middle and upper parts of the plume. The detection threshold of the data is dependent more on repeatability noise than theoretical resolution issues. Preliminary assessment of the 1999/94 datasets suggests that CO_2 accumulations of less than 4000 m^3 (~2800 tonnes) can be detected.

Amplitudes

Figure 3 shows images of an inline from the different (time-lapse) seismic surveys at 1994, 1999, 2001 and 2002. The consistency between the data, including the nine different levels of CO_2 that have been identified, is striking with only minor differences between the 2002 and the 2001 datasets.

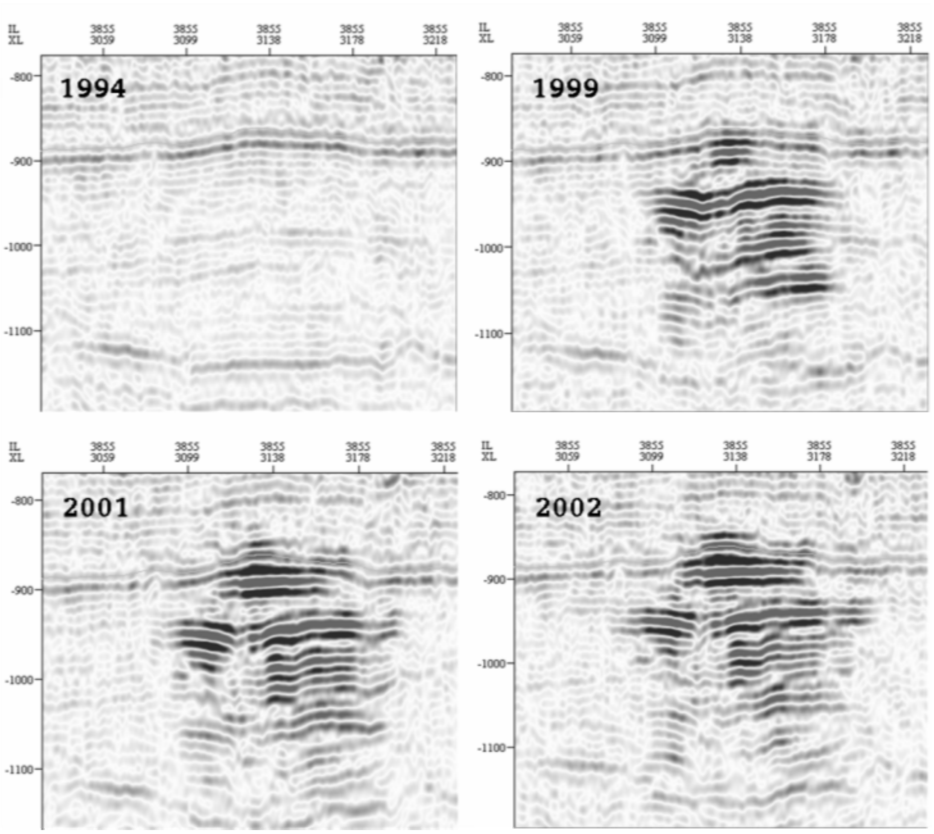

Figure 3: Inline from the four different seismic vintages acquired in 1994, 1999, 2001 and 2002. The effect of the CO_2 is clearly visible as strongly brightened layers.

Figure 4 shows the nine identified CO_2 levels as interpreted on the seismic data [9 to 12]. The most marked growth of the accumulations has taken place at level 9 (the topmost level) and level 5 (the largest accumulation in the middle of the reservoir). Interpretation of the southern part of levels 7 and 8 is not straightforward. Thus apparent changes in level 8 stem from the fact that reflectivity interpreted on the 2001 data as level 8 has been reinterpreted on the 2002 data as level 7. The actual distribution of CO_2, however, has not changed so radically. The elongated migration pathway in the north-east of level 9 is interesting and is evident on the pre-injection seismic data as a subtle linear structural elevation (Figure 5). Whether this feature is purely stratigraphical or has some structural control is still uncertain.

As observed earlier on the 2001 data [12], the deeper CO_2 accumulations, seem to be approaching a steady state. This observation is consistent with the thin shale layers within the reservoir having some form of distributed effective permeability. Thus a CO_2 accumulation beneath a thin shale bed would grow laterally until flow through the shale just balances input from below. At this stage lateral spreading ceases, with the CO_2 accumulation in dynamic equilibrium.

Key tenets of the quantitative analysis so far carried out [9 to 12] are that the CO_2 is ponding in high-concentration layers below thin shale layers and that the thickness of the individual accumulations can be estimated using a thin-layer tuning relationship. So far this theory has only been sustained by seismic modelling and by reservoir simulation. Currently the topmost CO_2 accumulation, just below the seal, has grown sufficiently to provide an independent verification of the "tuning assumption". At this uppermost level, the seismic signal is not distorted by pushdown effects due to overlying CO_2 and a reliable structural analysis can be performed. Figure 6 shows an amplitude map of the 2002 seismic data at the top of the reservoir together with a structural interpretation, in depth, of the top of the reservoir from the 1994 seismic data.

The structural interpretation has been truncated at a depth level of 797 m with the shallowest level at 789 m. Thus, if we assume that the base of the CO_2 layer corresponds to a flat CO_2-brine interface at 797 m depth, the colours indicate the approximate thickness of the CO_2 accumulation (based on topography), which ranges from 0 to 8 m. Note that the eight m thickness has been identified from earlier work [9,11,12] as the maximum tuning thickness. The correlation of the seismic amplitude map with the constructed thickness map is striking. The outlines are in good agreement and the high seismic amplitudes correspond to the structurally high areas, where the thickest CO_2 accumulations are expected. Only in the southern part of the accumulation is there a clear difference between the structure map (below the contact level of 797 m) and the amplitude map. This difference is caused by the migration pathway of the CO_2 up to the top of the reservoir. The CO_2 initially impinges on the top of the reservoir roughly above the injection point, south of the top of the structure (1999 interpreted level 9, Figure 4). From there it migrates laterally to the structurally highest point. Further work on calibration of layer thicknesses is ongoing, helping to increase confidence in the tuning relationship and in the fact that CO_2 does accumulate at high saturations below the shale beds.

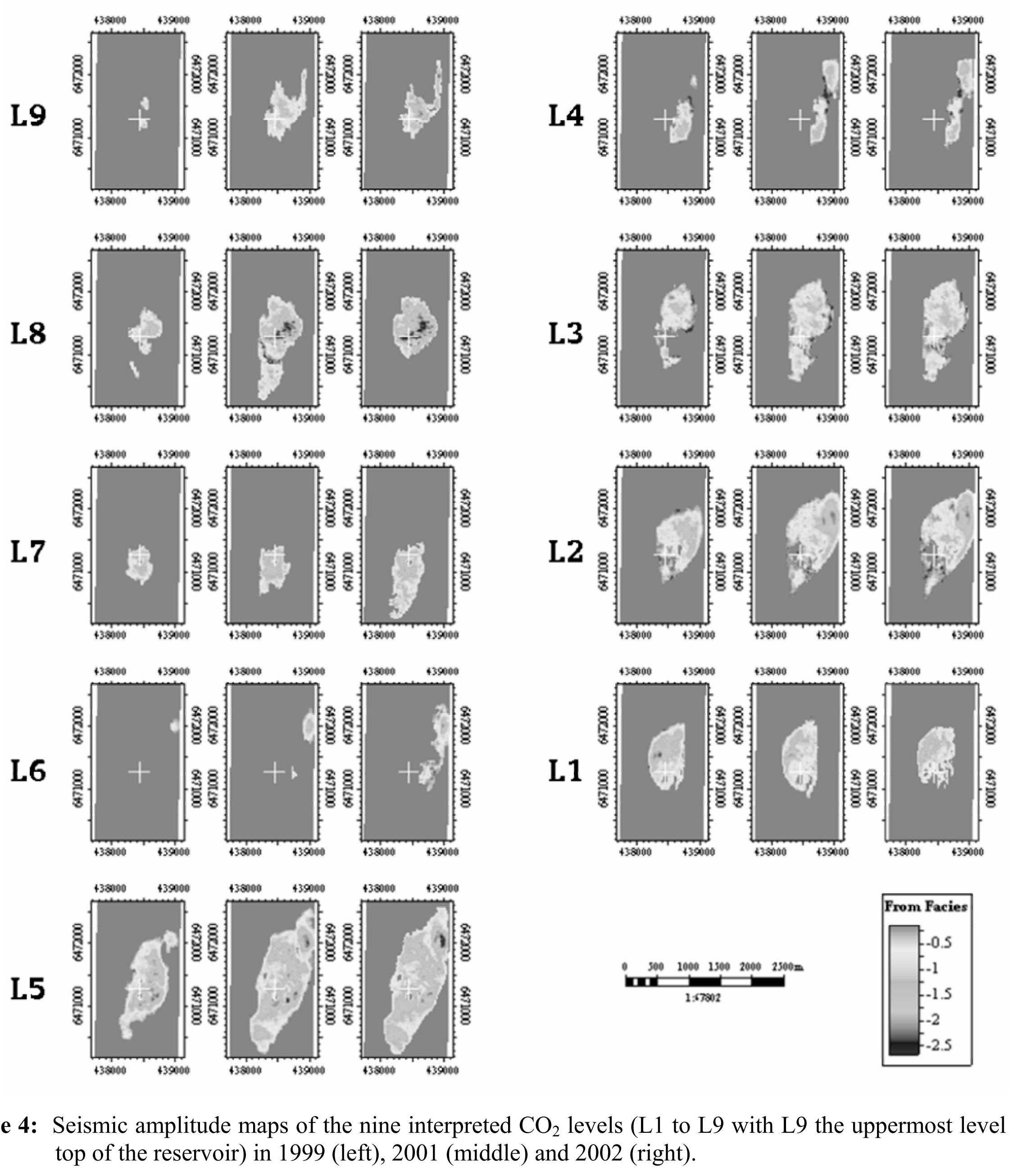

Figure 4: Seismic amplitude maps of the nine interpreted CO_2 levels (L1 to L9 with L9 the uppermost level at the top of the reservoir) in 1999 (left), 2001 (middle) and 2002 (right).

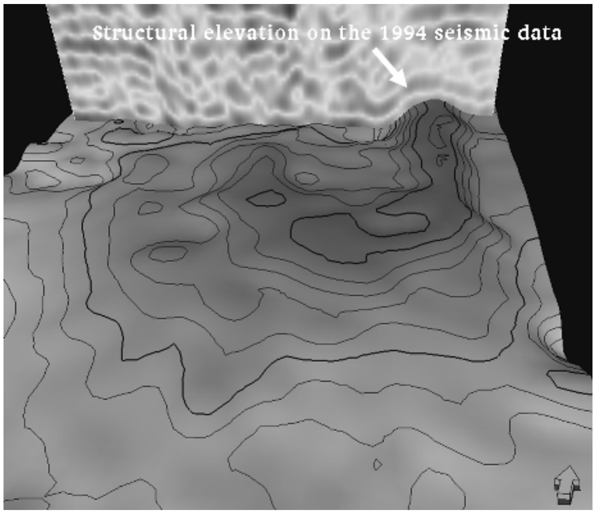

Figure 5: Visualization of the top reservoir horizon in TWT showing the elongated north-trending CO_2 migration pathway, together with a xline from the baseline 1994 seismic data prior to CO_2 injection.

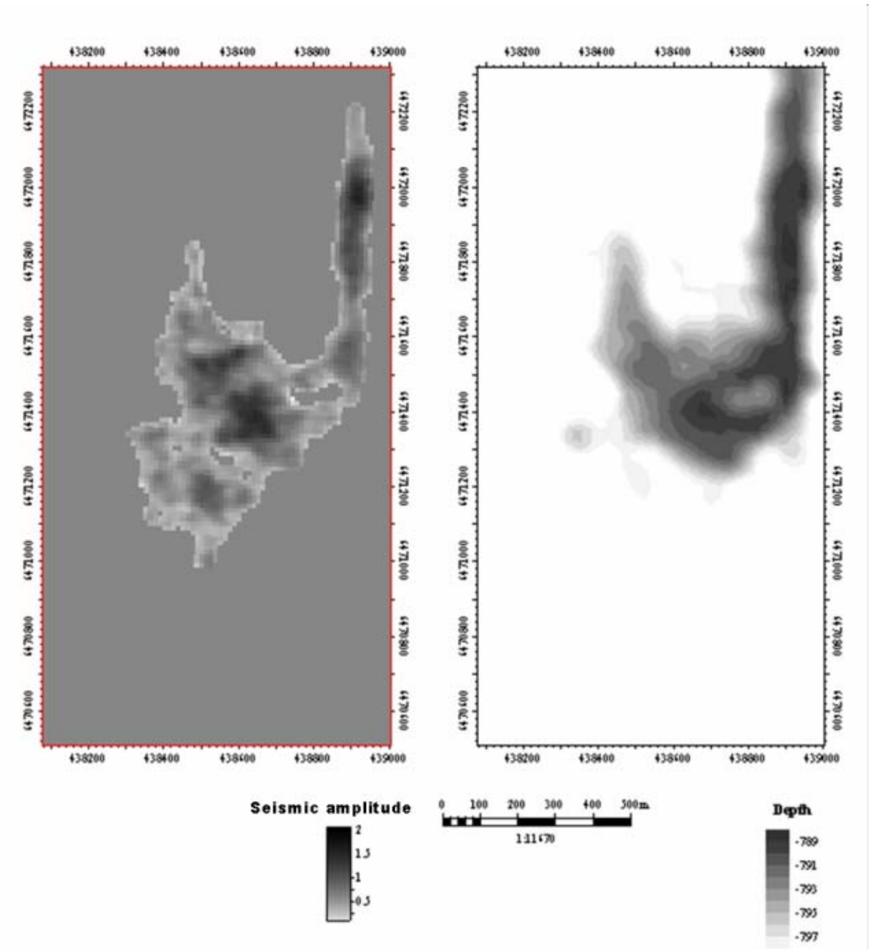

Figure 6: Amplitude map of the 2002 seismic data at the top of the reservoir (left) compared with the structural interpretation in depth of the top of the reservoir from the 1994 seismic data (right). The interpretation has been truncated at a depth level of 797 m with the shallowest level at 789 m. Assuming a flat CO_2-brine interface at 797 m, the colours show the thickness of the CO_2 accumulation (based on topography) ranging from about 0 to 8 m. The constructed thicknesses correlate well with the seismic amplitudes.

Pushdown

The second main seismic feature observed on the seismic data is the velocity pushdown caused by seismic velocities in CO_2-saturated sandstone being much lower than in brine-saturated sandstone (pressure effects on the seismic velocities are expected to be negligible, since no significant increase in pressure has so far been observed during the injection process). With 100% CO_2, saturation the velocity reduction with respect to 100% brine saturation is in the order of 30% [9, 10]. Figure 7 shows the measured pushdown for different time intervals.

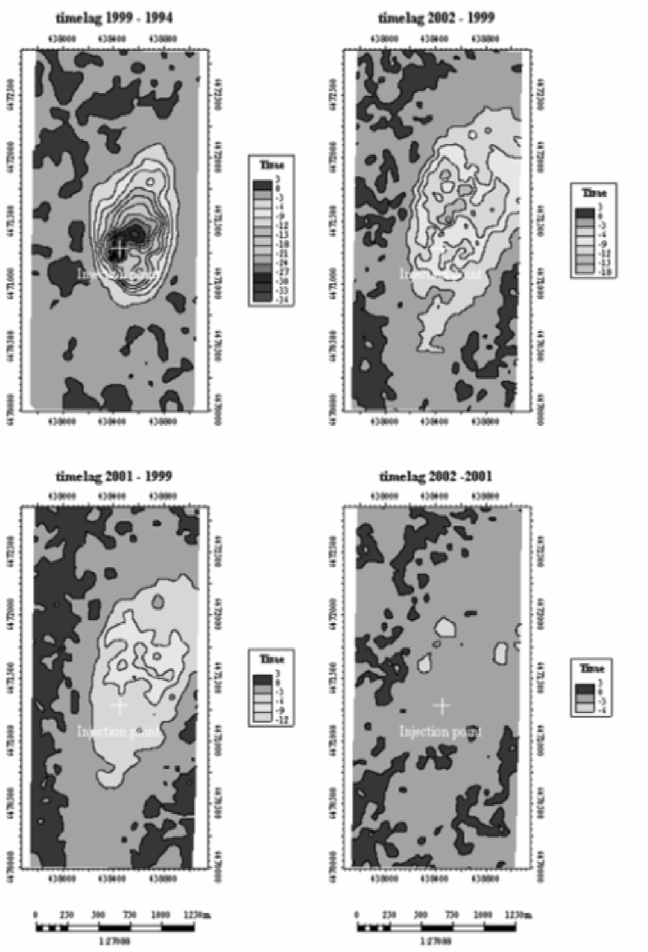

Figure 7: Pushdown maps as observed on the time-lapse seismic data covering different time periods.

The pushdown has been determined by a windowed cross-correlation of the post-stack time-lapse data with an earlier survey (either the base survey or an earlier time-lapse survey). The time window is fixed below the CO_2-injection point and thus below the CO_2 plume. Determining the peak of the cross-correlation function together with its corresponding time lag enables velocity pushdown to be mapped. A quality check of the determined pushdown has been performed by adding the calculated pushdown to the base Utsira Sand pick, interpreted on the baseline seismic data of 1994, and comparing the result with the interpreted base Utsira on the corresponding time-lapse survey. An example is shown in Figure 8. The interpretation of the 1994 base Utsira Sand plus the determined pushdown over the time interval 1994 to 2002, shows a good match with the 2002 time-lapse seismic data.

From Figure 7, it is clear that most pushdown developed from 1994 to 1999. From 2001 to 2002, the incremental pushdown is small. This supports our contention that a near steady-state flow upwards through the reservoir was reached by 2001 and that much of the injected CO_2 is now spreading laterally in the middle and upper parts of the plume in high-saturation layers.

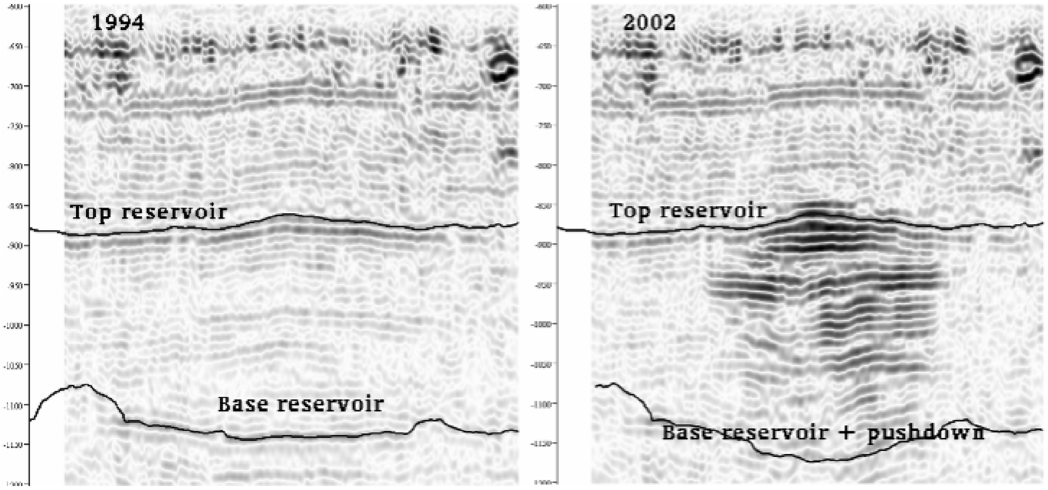

Figure 8: Inline as in Figure 2 showing the 1994 seismic data compared with the 2002 data. The interpretation of the 1994 base Utsira (left) summed with the determined pushdown over the time interval 1994 to 2002 (right) show a good correlation with the 2002 time-lapse seismic data.

Quantitative analysis of pushdown and reflectivity [9, 11 to 14] has shown whilst the plume reflectivity can be explained by CO_2 present as thin layers, the velocity pushdown observed beneath the plume is too large for the known in situ amount of CO_2 to be present only at high saturations. A significant component of lower saturation, or diffuse, CO_2 is also required, a key point being that relatively small volumes of CO_2 at low saturations produce large amounts of pushdown. The small-scale distribution of the low-saturation CO_2 is important for the saturation-velocity relation. The Gassmann equations ([15]) assume a homogeneous mix of fluids, but a more patchy distribution [16] would give a more linear velocity-saturation relationship, with a less extreme reduction in seismic velocity at low saturations. Pushdown patterns calculated from reservoir simulation results ([14]) indicate that patchy CO_2 distributions may well be significant in parts of the plume. Improvement of the history match between the seismically derived saturation distributions and the reservoir simulations is an iterative process and still in progress. The observed pushdown can at least be explained within the bounds of uncertainty between the extreme Gassmann model versus the patchy saturation model.

DISCUSSION AND CONCLUSIONS

The most recent 2002 seismic monitoring data still show no evidence of CO_2 migration above the top of the Utsira Sand. A near ‘steady state” flow upwards to the top of the reservoir seems to have been reached by 2001 and most of the CO_2 injected from 2001 to 2002 has spread laterally at the mid level (level 5) and at the top level (level 9). This is in agreement with the very small additional pushdown observed during that same period.

An independent verification of the thin-layer tuning relationship has been carried out at the top of the reservoir. Assuming that CO_2 accumulation follows the top-reservoir topography, the agreement between seismic amplitudes (related directly to CO_2 thickness) and the top structure map is good. This increases confidence in the presence of high-saturation accumulations of CO_2 just below the different shale layers.

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REFERENCES

1. Gregersen, U., O. Michelsen, and J.C. Sørensen. 1997. Stratigraphy and facies distribution of the Utsira Formation and the Pliocene sequences in the northern North Sea. *Marine and Petroleum Geology*, Vol. 14: 893-914.
2. Chadwick, R.A., S.Holloway, G.A. Kirby, U. Gregersen, and P.N. Johannessen. 2000. The Utsira Sand, Central North Sea – an assessment of its potential for regional CO_2 disposal. In: Williams, D., B. Durie, P. McMullan, C. Paulson, and A. Smith (eds.): *Proceedings of the 5th International Conference on Greenhouse Gas Control Technologies*, Cairns, Australia, CSIRO Publishing: 349-354.
3. Chadwick, R.A., P. Zweigel, U.Gregersen, G.A. Kirby, S. Holloway, and P.N. Johannessen. 2003. Geological characterisation of CO_2 storage sites: lessons from Sleipner, northern North Sea. In: Gale, J. and Y. Kaya (eds.): *Proceedings of the 6th International Conference on Greenhouse Gas Control Technologies*, Pergamon: 321-326.
4. Zweigel, P., R.J. Arts, A.E. Lothe, and E. Lindeberg. 2004. Reservoir geology of the Utsira Formation at the first industrial-scale underground CO_2 storage site (Sleipner area, North Sea). In: Baines, S.J. and R.H. Worden (eds.): *Geological Storage of CO_2 for Emissions Reduction*. Geological Society, London, Special Publication, 233.
5. Arts, R.J., P. Zweigel, and A.E. Lothe. 2000. Reservoir geology of the Utsira Sand in the Southern Viking Graben area – a site for potential CO_2 storage. *62nd EAGE Meeting,* Glasgow, paper B-20.
6. Eiken, O., I. Brevik, R. Arts, E. Lindeberg, and K. Fagervik, 2000. Seismic monitoring of CO_2 injected into a marine aquifer. *SEG Calgary 2000 International Conference and 70th Annual Meeting*, Calgary, paper RC-8.2.
7. Brevik, I., O. Eiken, R.J. Arts, E. Lindeberg, and E.Causse. 2000. Expectations and results from seismic monitoring of CO_2 injection into a marine aquifer. *62nd EAGE meeting*, Glasgow, paper B-21.
8. Arts, R., I. Brevik, O. Eiken, R. Sollie, E. Causse, and L. van der Meer. 2000. Geophysical methods for monitoring marine aquifer CO_2 storage – Sleipner experiences. In: Williams, D., B. Durie, P. McMullan, C. Paulson, and A. Smith (eds.): *Proceedings of the 5th International Conference on Greenhouse Gas Control Technologies*, Cairns, Australia, CSIRO Publishing: 366-371.
9. Arts, R, O. Eiken, A. Chadwick, P. Zweigel, L. van der Meer, and G. Kirby. 2004. Seismic monitoring at the Sleipner underground CO_2 storage site (North Sea). In: Baines, S.J. and R.H. Worden (eds.): *Geological Storage of CO_2 for Emissions Reduction.* Geological Society, London, Special Publication 233, 181-191.
10. Arts, R., R. Elsayed, L. van der Meer, O. Eiken, S. Ostmo, A. Chadwick, G. Kirby, P. Zweigel, and B. Zinszner. 2002. Estimation of the mass of injected CO_2 at Sleipner using time-lapse seismic data. *64th EAGE Meeting, Florence*, paper H016.
11. Chadwick, R.A., R. Arts, O. Eiken, G.A. Kirby, E. Lindeberg, and P. Zweigel. 2004. 4D seismic imaging of an injected CO_2 plume at the Sleipner Field, central North Sea. In: Davies, R., J. Cartwright, S. Stewart, M. Lappin, and J. Underhill (eds.): *3D Seismic Data: Application to the Exploration of Sedimentary Basins.* Geological Society, London. Memoir 29, 305-314.
12. Chadwick, R.A., R. Arts, and O. Eiken. (In press for 2005). 4D seismic quantification of a growing CO_2 plume at Sleipner, North Sea. In: Dore, A.G. and B. Vining (eds.): *Petroleum Geology: North West Europe and Global Perspectives – Proceedings of the 6th Petroleum Geology Conference.* Copyright Geology Conferences Ltd. Published by the Geological Society, London.
13. Lygren, M., E. Lindeberg, P. Bergmo, G.V. Dahl, K.A. Halvorsen, T. Randen, and L. Sonneland. 2002. History matching of CO_2 flow models using seismic modelling and time-lapse data. *Society of Exploration Geophysicists Annual Meeting*, Salt Lake City, October 2002. Extended Abstract. 4p.
14. R. Arts, O. Eiken, A. Chadwick, P. Zweigel, L. van der Meer, and B. Zinszner. 2004. Monitoring of CO_2 injected at Sleipner using time-lapse seismic data. *Energy*, 29, Elsevier Science Ltd, Oxford, 1383-1392.
15. Gassmann, F. 1951. Uber die Elastizitat poroser Medien. *Vier, der Natur*, Gesellschaft in Zurich, Vol. 96: 1-23.
16. Sengupta, M. and G. Mavko. 2003. Impact of flow-simulation parameters on saturation scales and seismic velocity. *Geophysics*, Vol. 68, No. 4: 1267-1280.