C1-1

MONITORING OF CO_2 INJECTED AT SLEIPNER USING TIME LAPSE SEISMIC DATA

R. Arts[1], O. Eiken[2], A. Chadwick[3], P. Zweigel[4], L. van der Meer[1], B. Zinszner[5]

[1] Netherlands Institute of Applied Geoscience TNO - National Geological Survey, PO Box 80015, 3508 TA Utrecht, The Netherlands.
[2] Statoil, R&D Centre, NO-7005 Trondheim, Norway.
[3] Britsh Geological Survey, Kingsley Dunham Centre, Keyworth, Nottingham, NG12 5GG, UK.
[4] SINTEF Petroleum Research, S.P. Andersens vei 15B, 7465 Trondheim, Norway.
[5] Institut Francais du Pétrole, 1 et 4 Av. de Bois-Préau, F-92852, Rueil Malmaison, France.

ABSTRACT

Since October 1996, Statoil and its Sleipner partners have injected CO_2 into a saline aquifer, the Utsira Sand, at a depth of approximately 1000 m. The aquifer has a thickness of more than 200 m near the injection site and is sealed by thick shales. A multi-institutional research project SACS (Saline Aquifer CO_2 Storage) was formed to predict and monitor the migration of the injected CO_2. To this end two time-lapse seismic surveys over the injection area have been acquired, one in October 1999 after 2.3 million tonnes of CO_2 had been injected and the second in October 2001 after approximately 4.4 million tonnes of CO_2 had been injected. Comparison with the base seismic survey of 1994 prior to injection provides insights into the development of the CO_2 plume. In this paper some selected results of the seismic interpretation of the CO_2 plume at the two different time-steps will be shown.

INTRODUCTION

CO_2 is injected near the base of the Utsira Sand at a depth of 1012 m below sea level. With the CO_2 in a supercritical state, the main mechanism driving its dispersion is gravity, the CO_2 rising buoyantly in the reservoir. The main barriers to this upward migration are thin intra-reservoir shales [1, 2], beneath which the CO_2 accumulates at high saturations.

The overall effect of the accumulated CO_2 on the seismic signal is significant [3]. By 1999 the CO_2 appeared to have reached the top of the reservoir. At several depth levels within the Utsira Sand a large increase in reflectivity has been observed on the time-lapse seismic data caused by individual CO_2 accumulations under the intra-reservoir, shale layers. The presence of these thin shales, which act as (at least temporary) barriers to flow, is evident from well data, but their effect on the 1994 (pre-injection) seismic signal is too small for a reliable lateral interpretation [3]. With CO_2 captured underneath, the shale layers are illuminated and can be identified on the seismic data as amplitude anomalies, despite the thicknesses of the accumulations being below the limit of seismic resolution. The enhanced reflectivity is mainly caused by the high compressibility of the CO_2 and by the constructive tuning effects of the top and bottom reflections at the CO_2 accumulations. The effect of the density is less important since the CO_2 is in a supercritical rather than a gaseous state at the reservoir P-T conditions. The thicknesses of the accumulations can be estimated quantitatively using the seismic amplitude information and assuming a tuning relationship [4, 5, 6].

Beneath the CO_2 plume a “velocity push-down effect” can be observed on the seismic data. This is due to seismic waves travelling more slowly through CO_2-saturated rock than through water saturated rock. In the first section of this paper the effect of CO_2 in the Utsira Sand on seismic velocities is explained using the Gassmann model [7, 8]. The consequences for the seismic data are then illustrated on synthetic models. Finally the results of the seismic interpretation of the CO_2 accumulations in 1999 and 2001 are discussed.

GASSMANN MODELLING

Seismic velocities were modelled as a function of CO_2 saturation using the Gassmann relationships [7, 8] which enable the elastic properties of a porous medium saturated with a fluid to be derived from the known properties of the same medium saturated with a different fluid. The densities and compressibilities of the saturating fluids, the rock matrix and the porosity of the rock are assumed to be known.

Figure 1 shows the modeling results for the velocities as a function of water (1-CO_2) saturation for three different bulk moduli. Laboratory experiments demonstrate, that the bulk modulus K is most likely << 0.675 GPa. This implies generally a fairly constant P-wave velocity < 1450 ms^{-1} for the Utsira sand for CO_2 saturations in the range of 20 – 100 % compared to a P-wave velocity of 2050 ms^{-1} for fully water saturated Utsira sand.

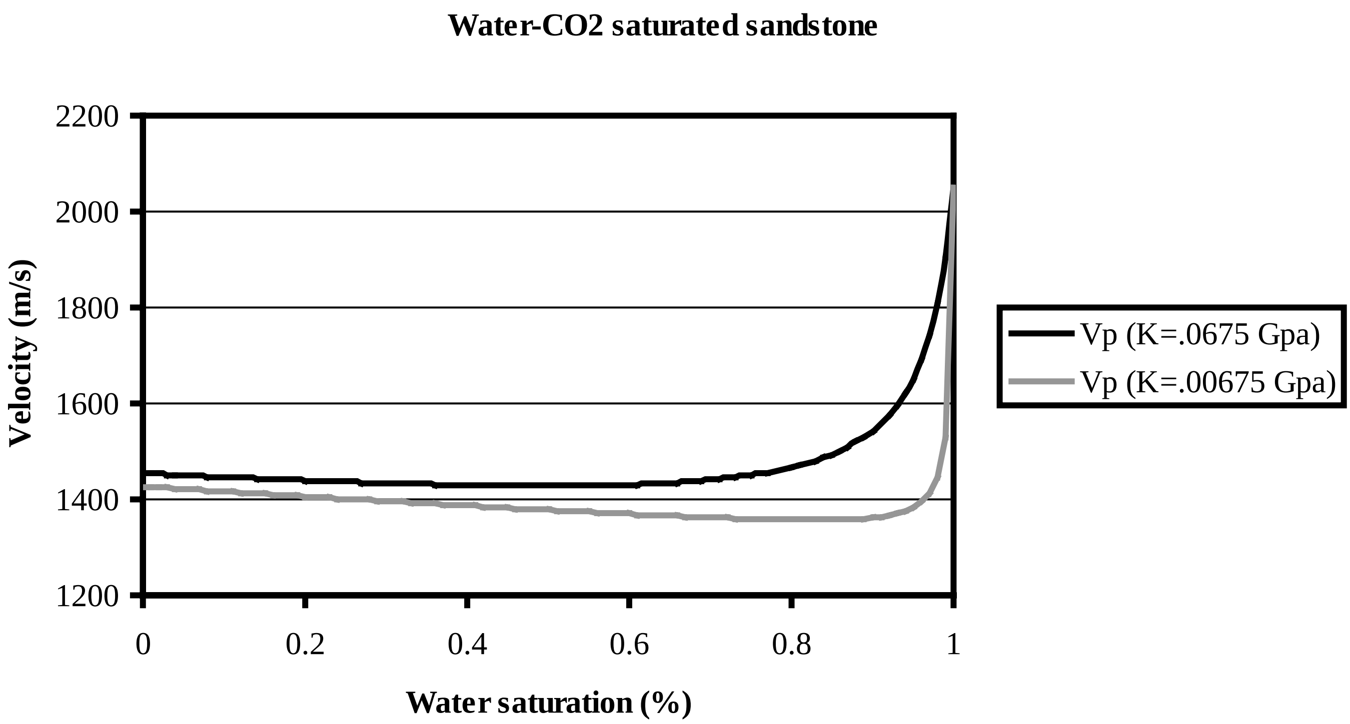

Figure 1: P-wave velocities of the Utsira Sand as a function of water- CO_2 saturation using Gassmann’s model.

SEISMIC MODELLING

In order to perform seismic modelling, a (zero-phase) wavelet was estimated from the seismic data. Using the estimated elastic parameters for the shale layers, for the 100% water saturated sandstone and for the (100%) CO_2 saturated sandstone, a simplified impedance model was created in order to predict the seismic response of the injected CO_2. Figure 2 shows an example of CO_2 accumulating under a thin (2m) intra-reservoir shale layer. CO_2 saturated sand with a range of thicknesses and a range of seismic wavelets (close to the estimated wavelet) was modelled in order to investigate the influence on the seismic signal.

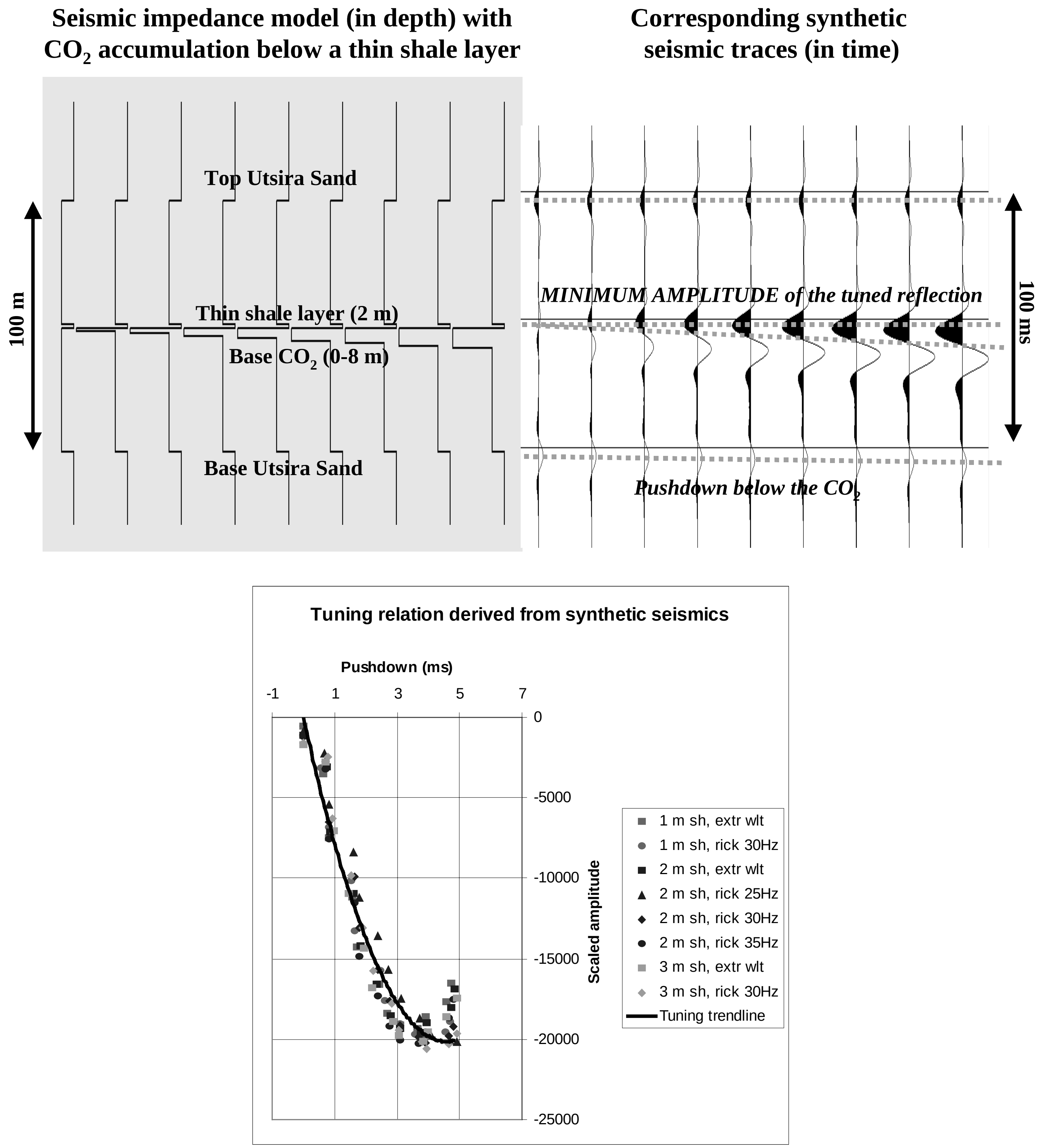

Figure 2: Simplified model of a variable thickness (0 to 8 m) of CO_2 beneath a thin shale layer (2 m) and the corresponding synthetic seismic response. In the diagram the seismic amplitude of the shale-CO_2 contrast is plotted against the pushdown below the CO_2 for varying shale thickness (1 to 3 m) and different seismic wavelets. A type of tuning relation can be distinguished.

Two dominant effects determine the seismic response:
- The negative seismic impedance contrast between the shale and the sandstone becomes more negative (larger in absolute value) when CO_2 is present.
- The seismic response is a composite wavelet caused by interference from sequences of water saturated sand, shale, CO_2 saturated sand and water saturated sand .

The first effect leads to stronger negative seismic amplitudes as for a classical “bright spot”. The second effect (tuning) can lead to destructive or constructive interference depending on the thickness of the CO_2 layer, evident from the seismic modelling. As the thickness of the CO_2 column increases a gradual increase of the (negative) amplitude is observed. Maximum constructive interference corresponds to a CO_2 thickness of about 8 m, the so-called ‘tuning thickness’

SEISMIC INTERPRETATION

As expected from seismic modelling, introducing CO_2 into the Utsira Sand has a dramatic effect on the reflectivity. This is illustrated on Figure 3 showing the seismic inline (of the 1994, 1999 and 2001 survey) through the injection point. At up to nine depth levels strong negative reflections (black peaks) are observed both on the 1999- and the 2001 time-lapse surveys. The consistency between the CO_2 levels of both vintages is striking. In general the 2001 CO_2 levels have a larger lateral extent and have been “pushed down” slightly more with respect to the 1999 CO_2 levels. This can be easily explained considering that more injected CO_2 causes more pushdown.

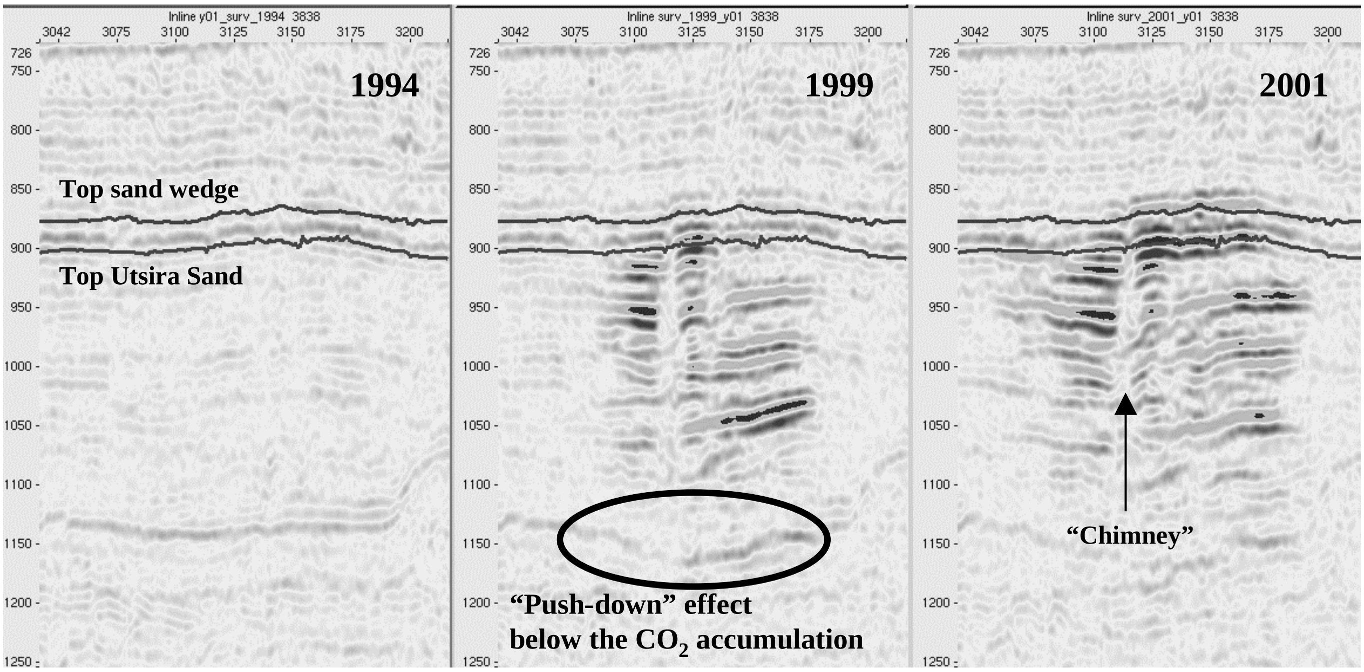

Figure 3: An inline through the injection area for the 1994, 1999 and the 2001 surveys.

The two shallowest CO_2 reflections correspond to accumulations at the top of the sand wedge and the top of the Utsira Sand. By 1999 the CO_2 had reached the top of the sand wedge and since then has spread laterally at this level. The other seven interpreted levels are caused by CO_2 accumulated below the thin intra-reservoir shale layers. Note that the reflections of these thin shale layers on the 1994 baseline data are too weak for a reliable interpretation; only when illuminated by underlying CO_2 is their interpretation possible.

A prominent vertical feature that can be clearly distinguished is characterized by localized pushdown and much decreased reflection amplitudes. This is interpreted as a “chimney” of CO_2, situated approximately above the injection point and forming a major vertical migration path which conducts CO_2 almost directly to the top of the reservoir.

The tuning effect as described in the previous section is illustrated in Figure 4. For this figure, locations have been selected in the 1999 and 2001 surveys, where only a single shale layer with CO_2 captured underneath is present. As expected these locations are concentrated towards the outer limits of the CO_2 plume. Note that the only criterion is the presence of a single shale layer, but not necessarily the same layer everywhere. For these selected locations the “pushdown” in time (which for a single layer is linearly related to the thickness of the CO_2 accumulation) has been plotted against the seismic reflection amplitude. The data appear to follow a tuning relation as expected from the synthetic seismic modeling.

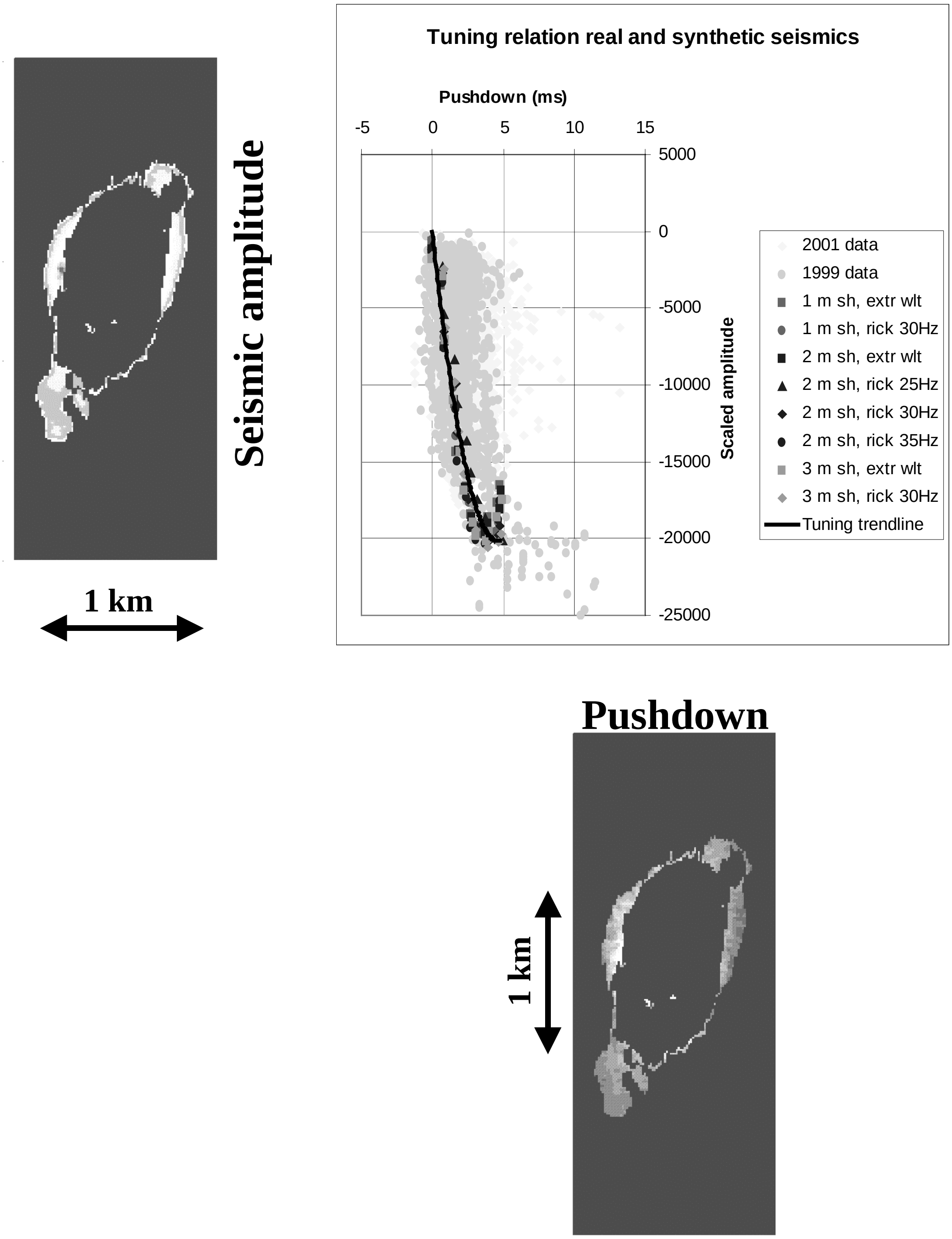

Figure 4: Demonstration of the tuning relation derived from seismic data (1999 and 2001 surveys) originating from locations where only a single shale layer is present. The map views at these locations of the seismic amplitudes (left) and of the pushdown (down) show the lateral extent of the total CO_2 accumulation at 1999.

In the real scattered data of 1999 and of 2001 a tendency exists of too high pushdown values with respect to the observed amplitudes. These values correspond most likely to locations where some “free CO_2” is present causing additional pushdown. Note that the relative scaling between the synthetic tuning curve and the observed data points is not fixed in absolute terms.

CONCLUSION

Time-lapse seismic surveying appears a highly 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 terms of seismic amplitudes and in observed velocity pushdown effects.

In addition to straightforward mapping of changes in the time-lapse seismic data, a number of quantitative approaches to mapping the supercritical CO_2 saturations have been carried out. The results have not been treated in this paper, but can be found in [4, 5, 6].

ACKNOWLEDGEMENTS

The SACS project was funded by the European Community (Thermie program), by the industry partners, i.e.: Statoil, BP, Norsk Hydro, ExxonMobil, TotalFinaElf and Vattenfall and by national governments. The R&D partners are TNO-NITG (TNO-Netherlands Institute of Applied Geoscience – National Geological Survey), SINTEF Petroleum Research, BGS (British Geological Survey), BRGM (Bureau de Recherches Géologiques et Minières), GEUS (Geological Survey of Denmark and Greenland) and IFP (Institut Francais du Pétrole). The IEA-Greenhouse Gas Programme is involved in the dissemination of the results.

REFERENCES

1. Lindeberg, E., Zweigel, P., Bergmo, P., Ghaderi, A., & Lothe, A. (2000b): Prediction of CO_2 dispersal pattern improved by geology and reservoir simulation and verified by time lapse seismic. In*: D.J. Williams et al. (eds.): Greenhouse Gas Control Technologies*, *CSIRO Publishing*, *Collingwood, Australia*, pp. 372-377.
2. Meer, L.G.H. van der, Arts, R.J., Peterson, L. (2000). Prediction of migration of CO_2 injected into a saline aquifer: Reservoir history matching to a 4D seismic image with a compositional Gas/Water model. In: *D.J. Williams et al. (eds.): Greenhouse Gas Control Technologies*, *CSIRO Publishing*, *Collingwood, Australia*, pp. 378-384.
3. Eiken, O., Brevik, I., Arts. R., Lindeberg, E., & Fagervik, K. (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.
4. Arts, R., Elsayed, R., Meer, L. van der, Eiken, O., Ostmo, S., Chadwick, A., Kirby, G., Zinszner, B. (2002). Estimation of the mass of injected CO_2 at Sleipner using time-lapse seismic data. *64th EAGE meeting, Florence*, paper H016.
5. Arts, R, Eiken, O., Chadwick, R.A., Zweigel, P., van der Meer, L.G.H., Kirby, G. (submitted 2002): Seismic monitoring at the Sleipner underground CO_2 storage site (North Sea). Submitted to Geol. Soc. Spec. Publ. on underground CO_2-storage.
6. Chadwick, R.A., Arts, R, Eiken, O., Kirby, G.A., Lindeberg, E., & Zweigel, P. (submitted 2002): 4D seismic imaging of a CO2 bubble at the Sleipner Field, central North Sea. Submitted to Geol. Soc. Spec. Mem. on 4D seismic.
7. Gassmann, F. (1951). Uber die Elastizitat poroser Medien. Vier, der Natur, Gesellschaft in Zurich, **96**, 1-23.
8. Mavko, G., Mukerji, T., Dvorkin, J., 1998. The rock physics handbook (pp. 168-170).