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Planning Time-lapse CSEM-surveys for Joint Seismic-EM Monitoring of Geological Carbon Dioxide Injection

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SUMMARY

Using state of the art survey planning and modeling tools, we investigate the possibility of employing marine controlled-source electromagnetic (CSEM) surveys in the monitoring of carbon dioxide sequestration. As a site example, we use the CO2 injection from the Sleipner Øst gas field into the Utsira formation in the North Sea. The injection plume inferred from 3D seismic surveys is used, together with well information and a priori geological knowledge, to build resistivity models for CSEM modeling. We find that the time-lapse change in the CSEM response would have been well above CSEM-acquisition noise levels in both 2001 and 2006. The combination of CSEM and seismic methods, which have a complementary dependence of their response on residual brine saturation, can yield an improved resolution of the CO2-distribution. In addition, CSEM methods are sensitive to the bulk volume of a resistor, also complementary to the superior resolution in seismics. We therefore would expect CSEM monitoring to become a valuable addition to the current monitoring program.

INTRODUCTION

The Sleipner Øst field is located about 250 km from the western coast of Norway, and operated by StatoilHydro. Gas from the Sleipner field contains about 9 mole % CO_2, which is separated prior to export. The separated CO_2, having a purity of about 98%, is injected into the Utsira formation, about 900m below the seabed. The water depth in the area is about 80m. Since injection started in 1996, around 10 million metric tons of CO_2 have been injected (Hansen et al., 2005). This is the world's first industrial-scale storage scheme for carbon dioxide and thereby an ideal location for testing methods for monitoring carbon dioxide.

Methods such as the time lapse seismic and ocean bottom gravity surveying have been applied to monitor the CO_2 plume distribution in the Utsira formation (Chadwick et al., 2006). Time-lapse seismic indicates that the injected CO_2 is trapped at high saturation at the top of the Utsira sand and also beneath a stack of thin shale layers within. Although these layers are clearly imaged, there are still uncertainties in the interpretation, such as the pushdown indicating that some CO_2 is also distributed between the layers (Eiken et al., 2000).

Methods to detect hydrocarbons via their resistivity through controlled-source electromagnetic (CSEM) surveys with a source towed above the seafloor and electromagnetic receivers dropped over a prospect or monitoring area were developed over the past decade (e.g., Eidesmo et al, 2002) and can, given a sufficient resistivity contrast of the injection plume, also be used to detect changes in CO_2 -distribution. Since resistivity has a different dependence on CO_2-saturation than seismic velocity, there is the potential in CSEM giving important complementary information on its spatial distribution in the subsurface, see the respective saturation dependencies in figure 1 (Eiken et al., 2000 and Hoversten et al., 2003).

In the present work, we have modeled the CSEM response of the Sleipner CO_2-plumes from 2001 and 2006. We have assessed both the detection and time-lapse evolution of the response and compared it to estimated uncertainties in the acquisition of time-lapse CSEM.

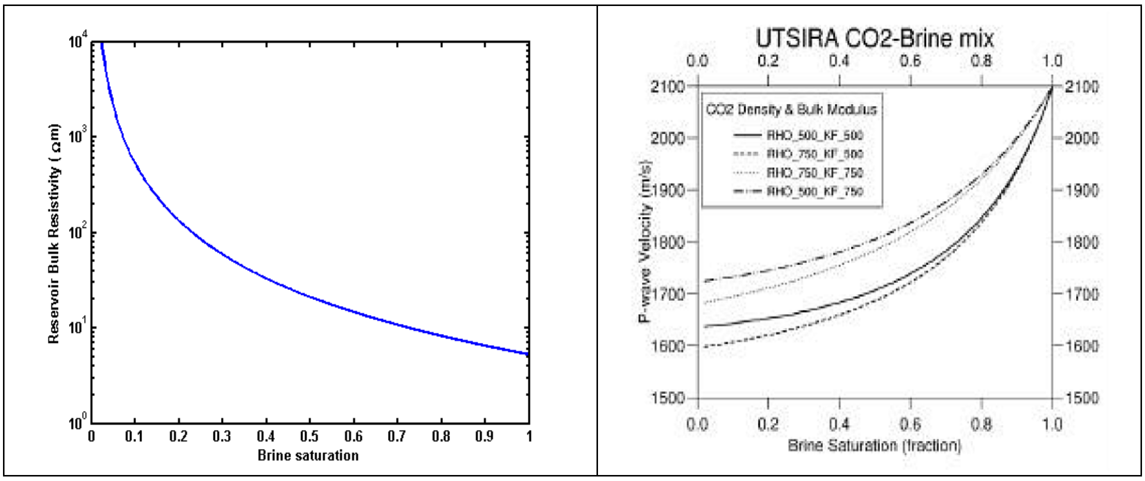

Figure 1: LHS: Resistivity versus brine saturation following Archie (1942). RHS: Seismic p-wave velocity versus the brine saturation (Eiken et al., 2000).

METHODOLOGY

Increasingly sophisticated CSEM survey designs (Thrane et al., 2007, Ridyard et al., 2006) and advanced processing techniques (e.g., Zach, et al., 2008, Støren et al., 2008, Bornatici et al., 2007) have been demonstrated recently, which puts its use for time-lapse monitoring into reach. We demonstrate the survey design for both a 2D grid and a line of receivers for a time-lapse CSEM survey above the Sleipner CO_2-injection area, along with a synthetic modeling based on geological models, with the CO_2-distribution inferred from the time-lapse seismic data from the years 1996-2006. All CSEM modeling presented has been generated with the methods described by Maaø (2007), and airwave-corrected using up-down separation (Roth, Zach, 2007).

The geological model was built from a 3D-seismic seafloor, known interpreted seismic horizons from Sleipner, well logs obtained from a nearby exploration well and the CO_2-injection well and, for larger depths, from the resistivity distribution known from general CSEM experience in the area. It was imported into a regular conductivity grid needed by CSEM forward modeling, with a resolution of (X, Y, Z) = (25m, 25m, 10m). The cross section of the model (without the CO_2-plume) is shown in figure 2. The most prominent features are the relatively low resistivity of the Utsira formation itself (<0.9Ωm), as well as the resistive chalk formation (5Ωm) known to be present at around 2.5km depth.

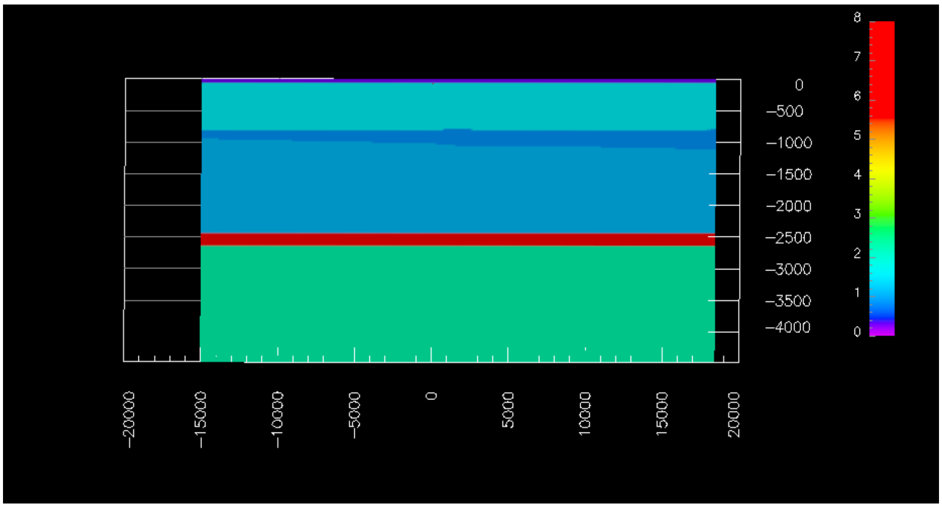

Figure 2: Background resistivity model for the Utsira formation in the vicinity of the Sleipner CO_2-injection plume (located at horizontal coordinate zero).

In light of the uncertainties otherwise present in the CO_2-injection area, the use of Archie's law (Archie, 1942) with a cementation factor of m=2 for the Utsira sands is justified for the purpose of survey planning. From log analysis of the CO_2-injection well, a porosity of $\phi=0.3$ was determined, which leads, following Archie, to an almost constant brine conductivity of $R_W=0.08\pm0.005\Omega m$ for the non-invaded Utsira sand. With the measured value of the residual water saturation $S_W=0.105$ (Ghanbari et al., 2006), this results in a resistivity of a completely CO_2-invaded zone of $R_t=(a\cdot R_W)/(\phi^m\cdot S_W{}^2)\approx 80\Omega m$. The seismic reflection amplitudes were converted to thickness assuming a linear-tuning response. After normalizing the total volume to the injected CO_2-volume, assuming a constant density of 700kg/m^3, an approximation of the thickness T for the CO_2-plume was thus obtained. The assumed constant resistivity $R_t=80\Omega m$ was mapped onto an integer number N of grid cells Δz for the CSEM forward modeling grid to maintain an approximately consistent CSEM response: $R\cdot(N\Delta z)=R_t\cdot T$.

A 2D survey grid with the methods described by Thrane et al., 2007 was designed for the known location of the CO_2-plume. The receiver locations are shown as blue points in figure 3. The attribute cube for the normalized magnitude-versus-offset for the 3D-CSEM survey with the inferred 2006-CO_2-distribution is visualized in figure 3, where synthetic data from the background model shown in figure 2 was used as a reference. The vertical axis represents the source-receiver offset, and the horizontal axes the source-receiver midpoint. The upper edge of the visualized plume corresponds to the upper edge of the Utsira formation. The assumed outline of the plume (light yellow dots on the surface) is mapped by the horizontal bulge of the 25%-contour of the attribute cube.

Figure 4 shows similar normalized magnitude- and phase difference-attributes for the time lapse signal, only for a constant thickness and resistivity of the CO_2-plume of 25m and 80Ωm, respectively. For clearer visualization, the response is plotted along the line of receivers shown as yellow dots in figure 3. The time-lapse responses for the 2001- and 2006-plumes versus the case without CO_2 are shown for an offset range of 3000m ± 250m. The peak anomalies are 25% and 50% respectively, which are both well above the time-lapse repeatability of 10%.

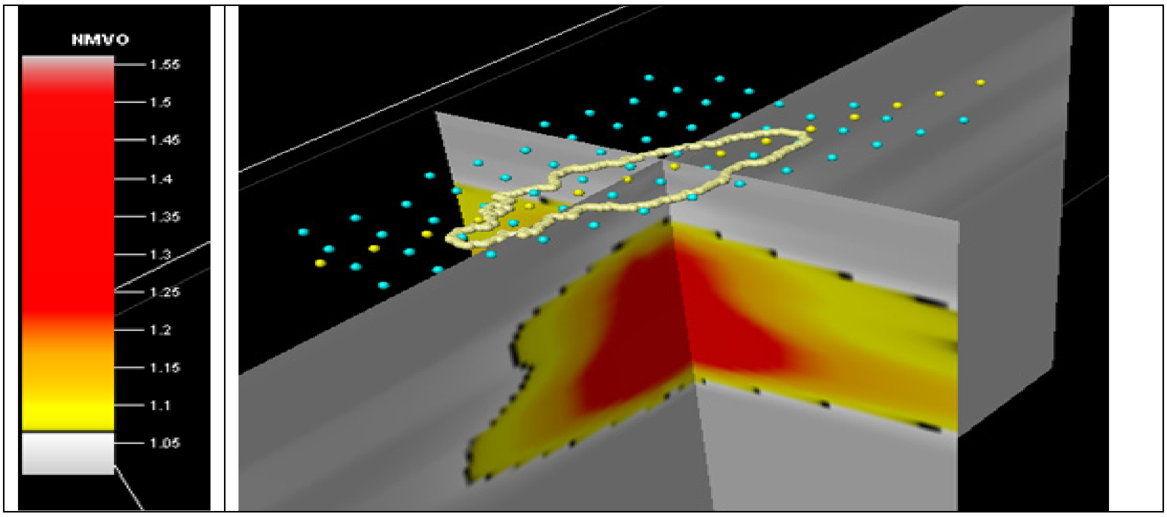

Figure 3: Color-coded visualization plot of the attribute cube for the normalized magnitude-vs.-offset cube of the up-down separated field at 1.0Hz from a CSEM reference modeling survey of synthetic data based on the 2006-CO_2-plume.

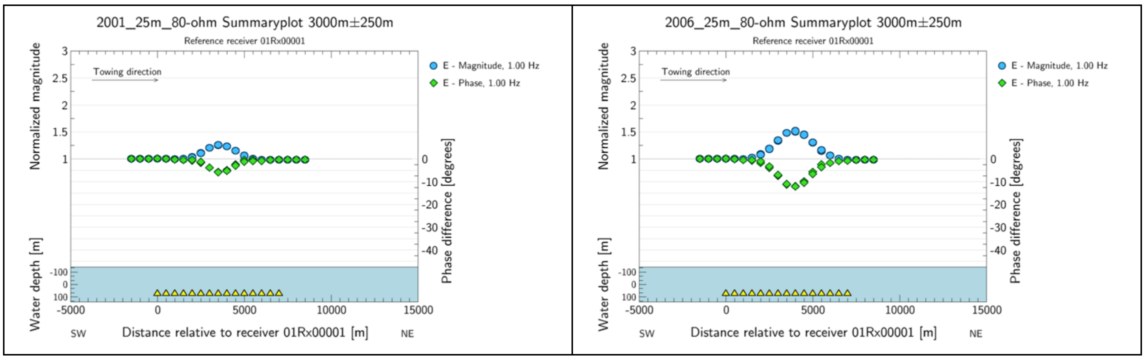

Figure 4: Normalized up-down separated-field (1.0Hz) magnitude and phase versus offset plots for the 2001- (LHS), and 2006-plume (RHS), with the model from fig. 2 as a background model.

Time-lapse repeatability effects can be categorized into geological & production-, and acquisition effects. Since the producing assets in the Sleipner area are at greater depths, and at a different lateral position, than the Utsira sands, signatures of the former can always be resolved with CSEM methods. Acquisition effects resulting from imperfect repeatability in towed lines are summarized in the measured curve shown in figure 5, which shows an example receiver signature for a repeatedly towed line from late 2007, showing a conservative upper limit of 10% time-lapse repeatability. The data do not include small-scale geological effects related to bathymetry, which becomes important if we do not manage to position the receivers exactly at the same locations. In the case of the relevant area of Sleipner, these should be negligible, as the bathymetry variations are smaller than, e.g., tidal fluctuations. Further, environmental factors such as seasonal variations in water temperature and salinity, which both affect salt water conductivity, must be taken into account. However, these can be very accurately quantified.

CONCLUSION

Based on experience from past marine CSEM surveys, and using survey planning and computational modeling methods developed over the past years, we have predicted the CO_2 injection from the Sleipner Øst field into the Utsira formation to be detectable in a future time-lapse CSEM survey. Together with time-lapse seismic surveys conducted at the same time, these will comprise complementary datasets due to the different dependence of the most relevant physical properties on the CO_2-saturation. This study has shown that EM imaging could play an important role in monitoring carbon dioxide storage.

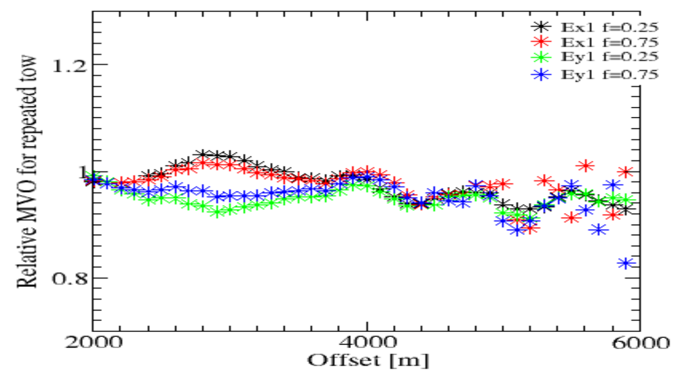

Figure 5: Typical and recent (late 2007) example for a measured time-lapse repeatability curve of a repeatedly towed CSEM line.

REFERENCES

- Archie, G.E. [1942] The electrical resistivity log as an aid in determining some reservoir characteristics. Trans. Am. Inst. Mech. Eng. 146, 54-62.
- Bornatici, L., Mackie, R., Watts, M.D. [2007] 3D inversion of marine CSEM data and its application to survey design. EGM 2007 Expanded Abstracts, Capri, Italy.
- Chadwick, A., Arts, R., Eiken, O., Williamson, P., Williams, G. [2006] Geophysical monitoring of the CO_2 plume at Sleipner, North Sea, in "Advances in the Geological Storage of Carbon Dioxide", NATO Science Series , Springer Netherlands, 303-314.
- Eidesmo, T., Ellingsrud, S., MacGregor, L. M., Constable, S., Sinha, M. C., Johansen, S. Kong, F. N. and Westerdahl, H. [2002] Sea bed logging, a new method for remote and direct identification of hydro carbon filled layers in deepwater areas. First Break, 20, 144-152.
- Eiken, O., Brevik, I., Arts, R., Lindeberg, E., Fagervik, K. [2000] Seismic monitoring of CO_2 injected into a marine aquifer. SEG 2000 Expanded Abstracts, Calgary.
- Ghanbari, S., Al-Zaabi, Y., Pickup, G.E., Mackay, E., Gozalpour, F., Todd, A.C. [2006] Simulation of CO_2 storage in saline aquifers. Trans IChemE, Part A, 764-775.
- Hansen, H., Eiken, O., Aasum, T.O. [2005] Tracing the path of carbon dioxide from a gas/condensate reservoir, through an amine plant and back into the subsurface aquifer – case study: the Sleipner area, Norwegian North Sea, Paper SPE 96742 (Offshore Europe 2005, Aberdeen, Scotland, UK, September 6-9, 2005, Proceedings).
- Hoversten, G.M., Gritto, R., Washbourne, J., Daley, T. [2003] Pressure and fluid saturation prediction in a multicomponent reservoir using combined seismic and electromagnetic imaging. Geophysics, 68, 1580-1591.
- Maaø, F. A. [2007] Fast finite-difference time-domain modeling of marine-subsurface electromagnetic problems. Geophysics, **72**(2), A19-A23
- Ridyard, D., Wicklund, T.A., Lindhom, B.P. [2006] Electromagnetic prospect scanning moves seabed logging from risk reduction to opportunity creation. First Break 24, 1-4.
- Roth, F., Zach, J.J. [2007] Inversion of marine CSEM data using up-down wavefield separation and simulated annealing. SEG 2007 Expanded Abstracts, San Antonio.
- Støren, T., Zach, J.J., Maaø, F. [2008] Gradient calculations for 3D inversion of CSEM data using a fast finite-difference time-domain modeling code, EAGE 2008, Rome, Italy (accepted).
- Thrane, B.P., Meissner, E., Panzner, M., Maaø, F.A. [2007] Effect of receiver density and azimuth data in grid modeling of seabed logging. 77th Annual International Meeting, SEG, Expanded Abstracts, 614-618.
- Zach, J.J., Roth, F., Yuan, H. [2008] Data preprocessing and starting model preparation for 3D inversion of marine CSEM surveys. EAGE 2008, Rome, Italy (accepted).