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CSEM sensitivity study for Sleipner CO_2-injection monitoring

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Abstract

The controlled-source electromagnetic (CSEM) method is a proven and promising geophysical technique in the hydrocarbon exploration area. Recently, there is increasing interest in applying it to CO_2-injection monitoring in both land and marine environments. For example, a marine CSEM survey has been carried out in the Sleipner area in 2008 to map the CO_2 plume in the Utsira formation. There are still scientific and technical issues to resolve and improve further. In the current study, we focus on two particular issues. The first is to explore the possibility of modeling the CO_2 plume in the Utsira formation at the Sleipner area by means of an effective anisotropic resistivity layer. The second is the application of so-called surface-to-borehole CSEM in order to increase the sensitivity of CSEM data to the CO_2 plume.

Keywords: CO_2-injection monitoring; Sleipner; CSEM; effective anisotropy resistivity; borehole EM

1. Introduction

The CO_2-injection at Sleipner has been ongoing since 1996 and every year around 1 million metric tons of supercritical-state CO_2 has been pumped into the Utsira formation with great success. The CO_2 plume development has been regularly monitored via time-lapse seismic data, imaging the spatial distribution of the injected CO_2 (Arts *et al*., 2008). In 2008, the controlled-source electromagnetic (CSEM) data has been for the first time collected along a single towline above the injection region, with the intention of estimating the *in situ* electrical resistivity of the injected CO_2. The conventional CSEM method acquires the EM fields on the seabed, generated by an electric transmitter towed just above seabed (surface-to-surface). The resistivity information makes it possible to predict the petrophysical state of the injected CO_2, e.g. saturation. However, there are two major challenges in interpreting the CSEM

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data collected in 2008: 1) there is no CSEM data acquired before injection; 2) it is expected that the resistivity anomaly of the CO_2 plume is rather small, i.e. around 5%, which is low in the sense of conventional surface-to-surface CSEM (Park *et al*., 2011).

In this study, we perform a sensitivity study in order to increase the confidence in our on-going interpretation/inversion work for the 2008 Sleipner CSEM data and to explore a new potential of CSEM for monitoring purposes. The sensitivity study is based on a synthetic, yet realistic, geological background model, which is created using deep induction logs (ILD) from wells in the Sleipner area. All the wells were drilled before injection. Herein we focus on two issues. The first is the average-sense anisotropic resistivity feature of the CO_2 plume in the Utsira formation (Park *et al*., 2011) to show that we can represent the CO_2 plume of 9 isotropic thin layers by means of an effective medium approach. The second is the application of so-called surface-to-borehole CSEM in addition to the conventional surface-to-surface CSEM. Recent research shows a potential of recording the EM fields within wells, which may increase significantly the sensitivity of CSEM data, particularly for reservoir monitoring purposes (surface-to-borehole, e.g. Kong *et al*., 2009). We compare the CSEM data sensitivity to explore the potential advantages of applying surface-to-borehole CSEM to the Sleipner CO_2-injection monitoring.

2. CSEM data over CO_2-injection site at Sleipner

The CSEM data has been acquired in 2008 along a line above the CO_2 plume in the Sleipner area (Figure 1). The survey is of a conventional configuration, i.e. surface-to-surface. A total of 27 seabed receivers are deployed, covering about 9.5km, and the total tow-line length is around 30km. One of the challenges in interpreting the dataset is that there are 6 groups of in total 9 seabed pipes crossing the CSEM survey line, which interfere significantly with the CSEM data (See Figure 2).

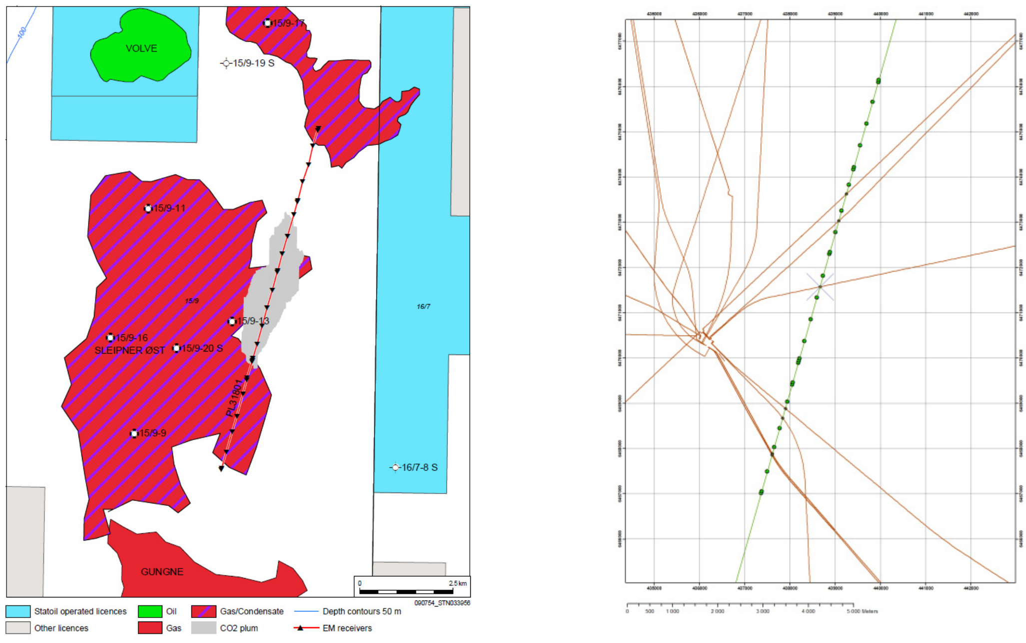
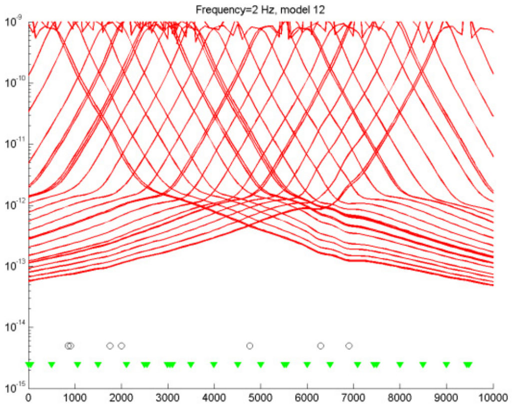


Figure 1. CSEM survey line on Sleipner area map (left) and 9 seabed pipes crossing the CSEM survey line (right). [provided by Statoil]

We are currently interpreting the dataset through various approaches (i.e. pseudo2D-, 2.5D-, and 3D-inversions) that is planned to finalize in 2012. Some preliminary results are published in 2011 (Park *et al*., 2011). Figure 2 shows the preliminary results as well as one set of the data at 2Hz. It is clearly shown in the left plot that the CSEM data strongly interferes with the seabed pipes. The three plots in the right show one example of resistivity profile result obtained through a pseudo2D-inversion approach. The CO_2 plume appears as a weak resistivity anomaly, located vertically at between 800m and 1000m depth and laterally at between 3km and 7km horizontal coordinate, which is consistent with the seismic data interpretation (Arts *et al*., 2008). It is also noted that the CO_2 plume shows a rather strong anisotropic feature (See the right-bottom plot in Figure 2).



2Hz E_{inline} fields at 27 receivers (red curves: E_{inline}; green triangles: 27 receivers; black circles: seabed pipe crossing points)

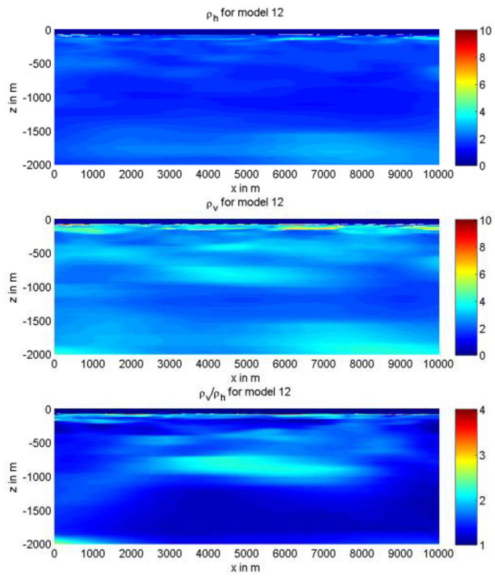


Figure 2. Example of CSEM data collected in 2008 (left) and pseudo2D or line-inversion result (right) [Park *et al*., 2011].

3. 3D resistivity model based on deep resistivity data

A geological model for the Sleipner area was generated to obtain a background resistivity model for the CSEM sensitivity study. The grid resolution is approximately 100m x 100m x 65m. The resistivity grid was populated using deep resistivity (ILD) well log data. The work started with seismic interpretation of appropriate reflectors confirming the well tops. Total 10 surfaces were interpreted using well tops from 5 wells containing check-shot data and located in the 3D seismic cube. From all the interpreted surfaces, horizons were generated as per Petrel™ workflow. The depth conversion was carried out using Linvel formula:

$$V=V_0+KZ \tag{1}$$

where V_0 = initial velocity of a particular surface or reference datum, V = final velocity, K = constant and Z = depth. Using the available check-shot data, the start value for Linvel function V_0 of each horizon was generated. Putting V_0 = 1480 for the water zone, a velocity model was iterated for horizons from top to bottom to get the well tops at exact depths.

On the basis of distinct deep resistivity (ILD) signatures, zones were defined and layering was carried out keeping in view the depositional environment of each zone. The deep resistivity (ILD) data was employed after up-scaling according to the zone divisions. Properties were distributed using Gaussian random function simulation for zones which had a random depositional character, e.g. Frigg turbiditic sands. Zones with depositional environments of continuous layering were populated using a moving average with appropriate orientation and major/minor ratio according to the possible depositional strike and direction. The final resistivity model is shown in Figure 3. The high resistivity features within and below Rogaland group are due to presence of carbonates.

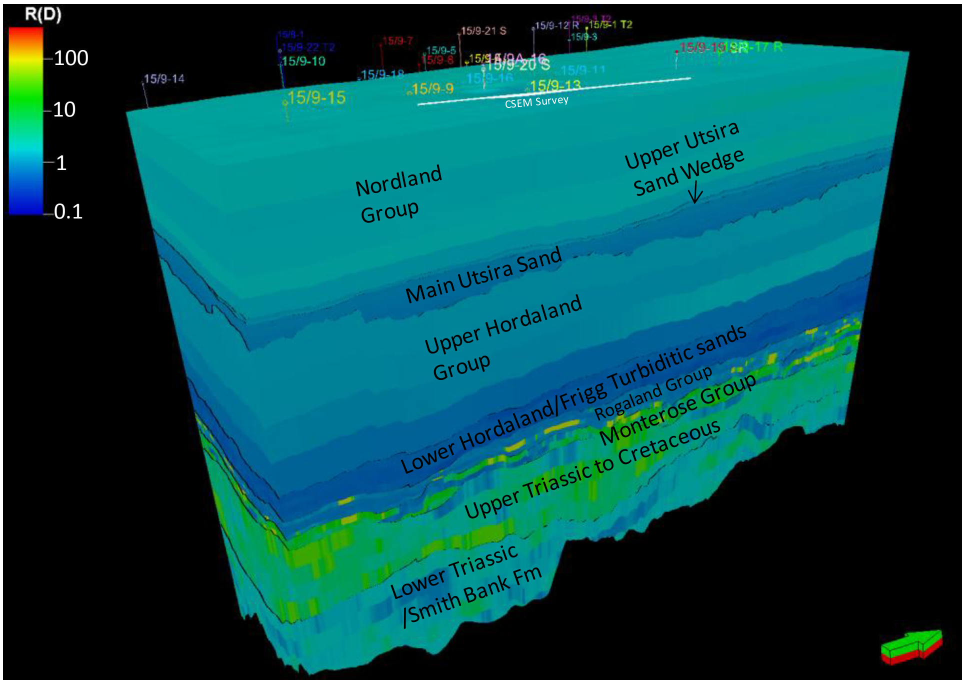
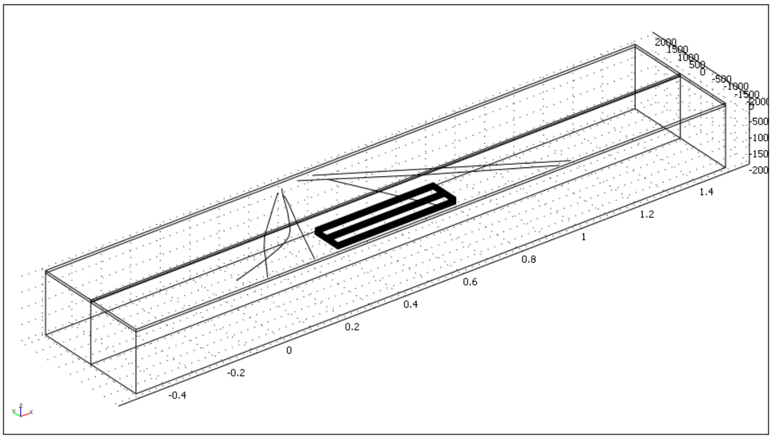


Figure 3. Final resistivity model. The white horizontal line shows the CSEM survey profile. High resistivity features within and below Rogaland group are due to presence of carbonates.

4. Effective-anisotropic thick layer for isotropic thin layers

Time-lapse seismic interpretation (e.g. Bickle *et al.*, 2007) shows that in the Utsira formation exists a set of 9 thin CO_2-saturated layers, each of which is around 2m thick, developed due to thin low-permeable mud-stone layers. Compared to the seismic data, the resolution of the CSEM data is relatively low, particularly when the target anomaly is weak such as in the Utsira case. Therefore, it may not be realistic to resolve those 9 CO_2-saturated thin layers through the surface-to-surface CSEM data. As shown in Figure 2, it may be the case that in the CSEM data interpretation/inversion, the 9 thin layers are observed as a single CO_2 plume layer of approximately 180m thickness and of relatively high anisotropic ratio (i.e. the ratio of the vertical to horizontal resistivity is high compared to the background). Therefore, it is important to understand the CSEM data sensitivity with respect to the potential resistivity anisotropy in the Utsira formation, which is done in this section. For this purpose, we use the realistic geological background model that is described in the previous section. We simulate the EM response of two types of resistivity domains (representing the CO_2 plume): one with 9 isotropic thin layers and the other with an effective-anisotropic 180m-thick layer. We compare the synthetic data resulting from the two simulations and investigate how to correlate the results of the two different types of target domains. This kind of correlation will help us in interpreting the results of the inversion as well as simplifying the inversion procedure (i.e. avoiding detailed modeling of complex geological structure).

To create the synthetic data, we use a finite element framework that is developed via the commercial software *COMSOL Multiphysics*. With the framework, we are capable of simulating full 3D geological models with high accuracy and perfect radiating boundary domain technique (Park *et al*., 2010). Figure 4 shows the main computational domain built in *COMSOL Multiphysics* (left) together with the two types of CO_2 plume domain (right). For the 9 isotropic thin layers model, the resistivities of each 2m-thick CO_2 layer and each 18 m-thick background layer of the Utsira formation are 23 Ωm and 1 Ωm, respectively. For the effective anisotropic layer model, the horizontal and vertical resistivities are 1.1 Ωm and 3.2 Ωm, respectively. These values are selected on the basis of the inversion results in Figure 2. For FE simulation, we apply an inline horizontal electric dipole source (HED) towed for x=−5 to +15 km and 30 m above seabed. The water depth is 80 m, which is close to the actual sea depth in the Sleipner area.



20km×4km×2km main computational domain contains 6 groups of seabed pipes on the seafloor (line segments) and 4km×1km×200m CO_2 plume region (long and thin box in the middle), whose depth is 800 m below seabed.

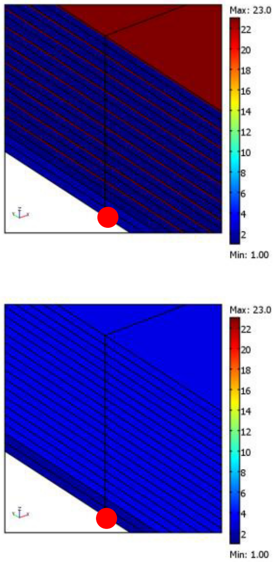


Figure 4. 3D FE model geometry for main computational domain (left); 9 thin-layers isotropic CO_2 plume (right upper); 180m-thick anisotropic CO_2 plume (right lower). The red circles represent the E_z receivers used in the next section (surface-to-borehole CSEM).

Figures 5 and 6 show the numerical results for the 9 isotropic thin layers model and the effective anisotropic thick layer model, respectively, in terms of so-called pseudo2D attribute. The pseudo2D attribute plot herein is constructed in the following steps: (1) deciding a reference set data (here, resulting from the background model i.e. with no CO_2); (2) obtaining the normalized amplitude-versus-offset (AVO) curves for all the receivers; (3) plotting all the normalized AVO curves at once in a 2D space in which the horizontal and vertical axes are the common-mid-point along the x-axis and half the offset, respectively. Notice that the difference between the two types of CO_2 plume domain is almost invisible, which confirms that we can apply the effective anisotropic thick layer model instead of the 9 isotropic thin layers model. The latter would require a much more demanding computational effort than the former.

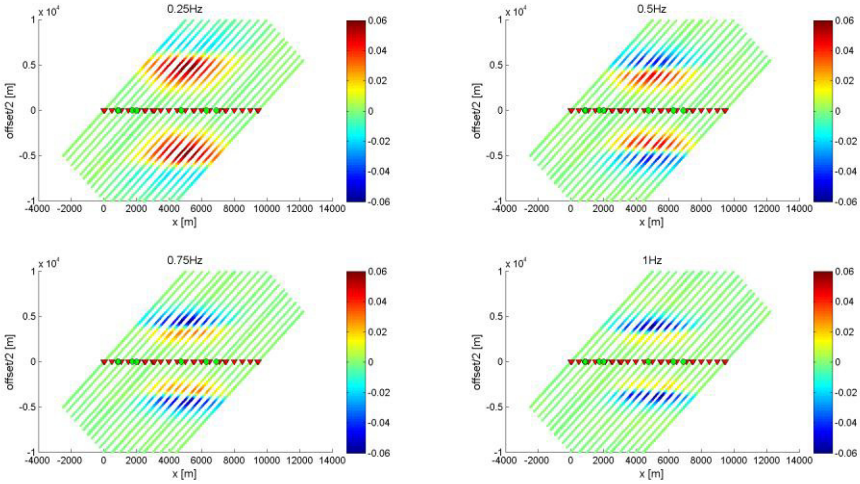


Figure 5. Surface-to-surface E_{inline} response due to CO_2 plume of 9 isotropic thin-layers, in terms of normalized amplitude with respect to background model.

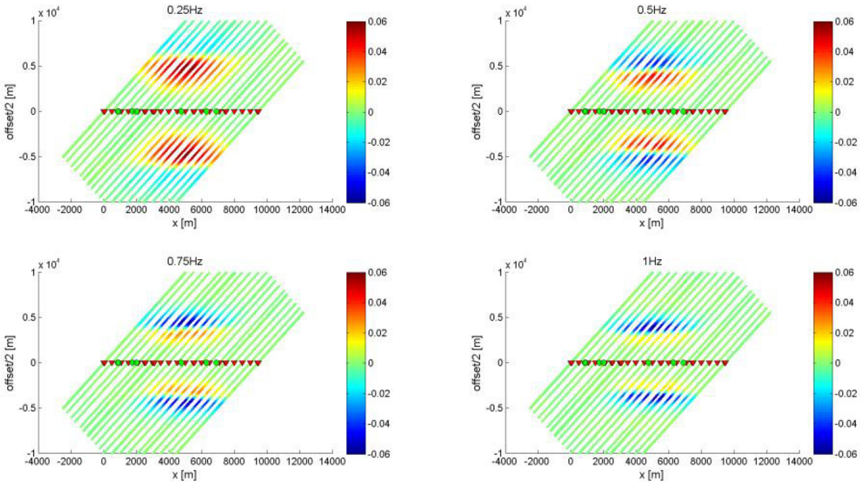


Figure 6. Surface-to-surface E_{inline} response due to CO_2 plume of effective anisotropic 180m-thick single layer, in terms of normalized amplitude with respect to background model.

5. Surface-to-borehole CSEM

Recently, so-called surface-to-borehole CSEM survey has become of great interest, especially for reservoir monitoring. The main advantage of the surface-to-borehole CSEM survey is that it can increase significantly the CSEM data sensitivity, mainly because either the transmitter or the receiver is placed near or within the target reservoir, in comparison to the conventional surface-to-surface CSEM survey. This advantage is relevant for the Sleipner case, particularly because the expected anomaly is very weak (probably close to the noise level of surface-to-surface CSEM data). In this section, we introduce a surface-to-borehole CSEM survey configuration into the models used in the previous section. Namely, we record the synthetic CSEM data ($E_{vertical}$) at one edge near the CO_2 plume bottom (red circles in Figure 4). The transmitter is applied in the same way as in the previous section. Again, we consider the two types of CO_2 plume domain as in the previous section.

Figure 7 shows the results in terms of the amplitude versus offset (AVO) curves and the normalized AVO curves with respect to the background model. It is clearly seen that the surface-to-borehole CSEM data sensitivity is much higher than those of surface-to-surface CSEM data. In addition, it is noted that even in the surface-to-borehole CSEM case, the effective anisotropy model can be applied in order to simplify the modeling procedure e.g. during inversion. Namely, the green and red curves are almost on top of each other.

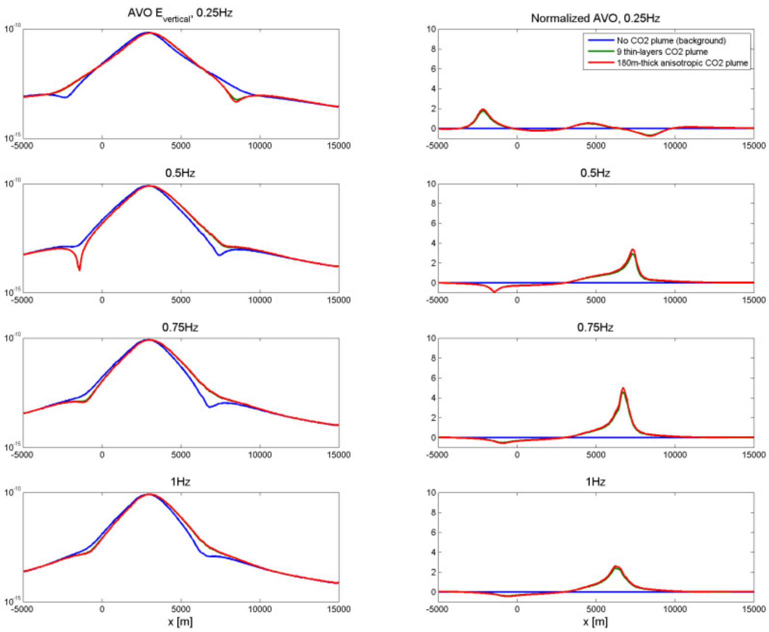


Figure 7. Surface-to-borehole CSEM $E_{vertical}$ response: absolute amplitude (left) and normalized amplitude with respect to background model (right).

6. Summary and remarks

In the current study we focus on two issues. The first is the average-sense anisotropic resistivity feature of the CO_2 plume in the Utsira formation (Park *et al.*, 2011). The second is the application of so-called surface-to-borehole CSEM in addition to the conventional surface-to-surface CSEM. For these purposes, we perform a set of numerical simulation study using a 3D finite element method (via *COMSOL Multiphysics*). It is learned that the effective anisotropic thick layer model can provide the equivalent CSEM data to the 9 isotropic thin layers model, which could simplify the on-going full 3D inversion. Also, through the second simulation study with surface-to-borehole CSEM configuration, we confirm that the surface-to-borehole CSEM survey could provide high sensitivity data, which will open up a new possibility of applying CSEM to CO_2 reservoir monitoring in the future.

Acknowledgements

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