2D Inversions of 3D Marine CSEM Data
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Summary
A combination of 3D forward simulations and 2D and 3D inversions have been used to demonstrate the appropriateness of applying 2D interpretation on data due to a 3D resistivity anomaly for a marine CSEM survey. This study is done in the first instance on a simple benchmark model. The results of synthetic modeling and inversion tests quantitatively show that the most important factors to properly use 2D inversions to characterize a 3D anomaly are: magnitude of the target’s CSEM response, the geometry, and the distance between its edge and the survey line.

Introduction
A marine Controlled-Source Electromagnetic (CSEM) survey is a useful tool for characterizing offshore hydrocarbon deposits because of its sensitivity to formation resistivity. The accuracy of the resulting interpretations can be improved if integrated with seismic and well log data. Due to the geometry of most subsurface targets, it makes sense to use a 3D methodology to derive the sub-sea resistivity structure and therefore 3D surveys tend to be preferred, if budget allows. In such surveys, several intersecting transmitter tow lines are laid out in the survey area with most receivers placed along the lines, but recording orthogonal electric fields so that a range of source-receiver geometries are acquired. However, 3D inversion of such a data set is still very computationally intensive (e.g., Gribenko and Zhdanov, 2007; Commer et al., 2008; Zach and Frenkel, 2009; Newman et al., 2010). In comparison, 2D inversion needs much less computation and results can be obtained in a much shorter period depending on the model grid and number of available data points. This approach rapidly provides resistivity images in a vertical section along the survey line and assumes an infinitely extending geology in the orthogonal direction. The method further provides a mechanism to construct starting models for 3D inversion to improve the efficiency of this process. However such 2D reconstructions can also provide valuable information in themselves. As a result of EM field attenuation in conductive media, 3D effects can be minimized with careful line placement and interpretation. In this study, we propose solutions that can help us to quantitatively determine ranges for which an inverted 2D image can adequately represent the 3D anomaly and how such results can be used to optimize a 3D interpretation approach. These results are compared with the results of full 3D inversion.

To achieve this goal, simple 3D models are simulated to generate 3D synthetic data sets along pre-selected CSEM tow lines and corresponding responses are compared to assess the 3D effects. Similar approach has been presented by Park and Bjørnarå (2011) however, we extend the scope of work by inverting the synthetic data, in both 2D and 3D, and comparing the results to the simulated models. For simplicity, we focus on the effect of the geometry of the model at a certain depth and tow line attitude relative to the resistivity anomaly. Although important in data interpretation, for simplicity anisotropy is not considered in this modeling study.

Model setup and simulation workflow
The basic model for generating synthetic data is shown in Fig. 1. The 20 Ωm anomaly is a flat, rectangular block with a thickness of 100 m, located 1500 m below the sea bottom. A 1000m-thick seawater layer with a resistivity of 0.31 Ωm is assumed, while the resistivity of the half space below the mud line is set to 1.0 Ωm. The in-line and cross-line dimensions of the anomaly (strike-length), denoted by $a$ and $b$, are varied for the simulations. Twenty one receivers are located at the sea bottom along the tow line at 1 km intervals. The transmitter, a horizontal electric dipole is towed 30 m above the sea bottom. Source frequencies are set to 0.125, 0.375 and 0.625 Hz.

An integral equation type 3D simulation based on that developed by Endo and Zhdanov (2008) is used to generate 3D synthetic data, which is also fed to 2D inversions. The amplitude and phase of the electrical maximal polarization ellipsoid at each receiver site are used as input for inversion. Our 2D code uses a finite-element based algorithm (Unsworth et al., 1993) as the forward engine and the Occam inversion (Constable et al., 1987) to derive resistivity distribution. The inversion is based on minimizing an objective functional composed of data misfit and model roughness. In this study all three source frequency datasets are included in the inversion with equal weighting.

Fig. 2(a) shows a typical marine CSEM response for a receiver located right above the center of a 3x3 km body (in this case, $a=3$ km, $b=3$ km, $s=0$). An assumed ambient noise level of $10^{-15}$ V/amp-m² is also displayed. At 0.125 Hz, the electric field magnitude is still above the noise level at a 10km separation while at 0.375 and 0.625 Hz the noise level is approached at about 6 and 5 km, respectively. Fig. 2(b)-(c) display the contoured normalized anomalous electric field for the simulated body for the three source frequencies. Here, the anomalous...
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values are obtained by subtracting the background field (without the rectangular prism) from the corresponding total field and normalized to the background field. Then we place each data point on the horizontal axis at the middle of the associated source-receiver pair and at a vertical distance equivalent to their separation. The normalized electric field anomaly reaches a maximum amplitude at about 7, 5.5, and 5 km source-receiver offsets, respectively, for the three frequencies. However, the highest frequency data is heavily contaminated by noise for this offset.

Effects of anomaly size

A prism of different sizes, 2x2x0.1, 3x3x0.1, and 4x4x0.1 km, is used to study the response of a 3D body of various lateral extensions. It is centered below the coordinate origin where the postulated west-east survey line goes through. As shown in Fig. 3(a) through 3(c), the larger the body, the larger the normalized response. Though the normalized response for f=0.625 Hz is the largest one, its absolute values can be close to the noise floor at longer offsets. 2D inversions of the synthetic data for the 2x2 km body demonstrated that this body could not be resolved using a 2D approach. The presence of the 3x3km body is recovered by the inversion (Fig. 3(d)). As might be anticipated, the fuzzy image is due to the application of smoothness regularization. While the horizontal location of the body is retrieved, its vertical position is about 200 m higher than its actual position. This is because the marine CSEM configuration does not have as good a resolving power in the vertical direction as in the lateral direction especially when a purely 2D approach is considered, and in the absence of independent structural information. Integrating seismic and/or log data will supply appropriate constraints to the inversions.

In the presence of noise results deteriorate markedly. For a model with a stronger response, such as the 4x4 km case, the target could be reasonably recovered (Fig. 3(e)) with 1% additive noise and with a 1.2 Ohm initial guess for the resistivity of the sub-sea half space (note that the true background resistivity is 1.0 Ohm). Based on this analysis, a 20% anomalous response at f=0.125 Hz is set as the criterion in the present study to determine if the anomalous body can be reliably recovered.

Effects of anomaly geometry

Reservoir geometry also has a significant effect on the CSEM response. Four cross line extents, namely b=3, 5, 7, and 9 km, are used for the simulated target with a common along-line width of 3 km. The last is deemed a 2D model. The survey line goes from west to east and passes over the center of the body. Fig. 4(a)-(c) illustrate the anomalous response for the three frequencies for source-receiver separations of 7, 5 and 3 km, respectively. It is to be noted that the response approaches the 2D value with increasing target extent across line. One may infer in this case that the resistivity anomaly can be treated as a true 2D body as long as the cross-line length of the model exceeds 5 km, because the inverted images of the 3x5 and 3x9 km synthetic data as displayed in Fig. 4(d) and (e), respectively, do not differ significantly (Fig. 4(f)). The derived vertical position is still about 200 m shallower than its actual position.

Fig. 5 shows the anomalous electric field (Ex) in the high resistivity body for four values of strike length, b. It is clear that the maximum anomalous field is independent of the value of b. This anomalous field will dominate the response observed at a receiver placed at the center of the body, supporting the assumption that for carefully designed survey layouts a 2D interpretation is appropriate.

Conclusions

Our study shows that 2D CSEM inversions can yield useful information about the structure of a 3D object under some favorable conditions: appropriate response magnitude and reasonable distance of the tow line from the edge of the target. Such 2D reconstructions provide a valuable first step in an interpretation process, and if undertaken carefully with appropriate seismic and well log constraints may in some circumstances meet the survey objectives without recourse to complex and time consuming 3D approaches. However the Earth is in reality a 3D realm, and ultimately 3D interpretation and inversion approaches, carefully conditioned by 1D and 2D reconnaissance modeling, are required.

Figure 1 A 100m thick rectangular block model and the source-receiver configuration. Here, a and b represent the anomaly’s in-line and cross-line dimensions, respectively, s is the distance between the surface projections of the target center and the survey line.
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Figure 3 (a) Electric field vs. source-receiver range for a receiver over the center of a 3x3km rectangular prism for the three source frequencies. Normalized anomalous electric field in contour plot due to the 3x3km body for (b) 0.125Hz, (c) 0.375Hz, and (d) 0.625Hz.

Figure 2 Normalized Anomalous electric field for 2x2x0.1, 3x3x0.1, and 4x4x0.1 km bodies for (a) 7 km separation at 0.125 Hz, (b) 5 km separation at 0.375Hz, and (c) 5 km separation at 0.625Hz. (d) The inverted image of the 3x3x0.1 km body without noise added. Note the horizontal coordinate is changed and 14 km corresponds to 0 in the top panels. (e) Inverted resistivity of the 4x4x0.1 km body with 1% noise added and a 1.2 Ω-m initial half space resistivity. The grey rectangle below the inverted anomaly is the simulated block.
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Figure 4 Normalized anomalous electric field for the block target with various dimensions, 3x3, 3x5, 3x7, and 3x9 km, for (a) 7000 m separation at 0.125 Hz, (b) 5000 m separation for 0.375 Hz, and (c) 5000 m separation for 0.625 Hz. The inverted images of (d) 3x5 km and (e) 3x9 km target. (f) The resistivity difference between (d) and (e). The grey rectangle below the inverted anomaly is the simulated block.

Figure 5 Total E_x at the center of the simulated anomaly along the strike direction.
EDITED REFERENCES
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