Inversion of marine Controlled Source Electromagnetic data using a “structure”-based approach.

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This paper was prepared for presentation during the 12th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, August 15-18, 2011.

Abstract

We present a fast “structure”-based inversion workflow for interpreting marine Controlled Source Electromagnetic (mCSEM) data, which reconstructs the resistivities and shapes of regions of interest using an inversion algorithm where the model is parameterized using both open and closed “structures”.

These *a priori* information may come from independent measurements (e.g., seismic) or from the results of an image-based inversion workflow.

We show that the “structure”-based inversion is capable of quantitatively reconstruct the resistivities and shapes of the regions of interest such as prospective reservoirs to obtain models that are consistent with both the mCSEM and the seismic data and that considerable improvement in resolution is achieved compared to the current state-of-the-art.

We illustrate the advantages and drawbacks of the “structure” inversion using both synthetic and real data acquired in the Santos Basin, offshore Brazil.

Introduction

For almost a decade, mCSEM has been offered as a prospect de-risking tool to the hydrocarbon exploration community and successful case studies have been reported worldwide (see: Hesthammer et al., 2010) and in the Brazilian deep offshore (Zerilli et al., 2010). The main focus has been to search for hydrocarbon indicators by tying local high resistive target responses derived from mCSEM to prospects mapped from seismic. State-of-the-art CSEM survey would typically make use of rather low frequencies (0.1 ~10 Hz) in order to penetrate the low resistivity overburden to reach the resistive targets at depths.

The importance of nonlinear inversion algorithms in the interpretation of mCSEM data has been pointed out by several authors due to their accuracy for high-contrast regions. A common way in the inversion process is to divide the domain of interest into sub domain with unknown parameters defined in each sub domain “cell” and then apply an optimization approach to match the responses between the data observed and the data generated from the estimated model. Several inversion algorithms have been proposed such as: (Abubakar et al., 2006, 2009; Commer and Newman (2008); Plessix and Mulder (2008)) to predict the resistivity distribution in each “cell”.

Method

In our development, we present a “structure”-based inversion scheme for interpreting mCSEM data, which reconstructs the resistivities and shapes of regions of interest based on *a priori* information. The required *a priori* information may come from independent measurements (e.g., seismic) or from the results of the same data using an image-based inversion approach (Abubakar et al., 2006). The results of the “structure”-based inversion can be considered as a projection of complex geological structures onto a certain low-dimensional model space. As an interpretation tool, the image-based inversion may provide a fast indicator of potential “anomalies” that can be used to produce starting and prior models for the “structure”-based inversion.

The “structure” inversion is based on a Gauss-Newton minimization technique with multiplicative regularization and a line-search scheme to stabilize the inversion process (Habashi and Abubakar, 2004). Here the shape of the various regions expressed as 2D “structures” defined by their vertices (nodes), can be reconstructed along with their locations and resistivities. The forward algorithm is based on a 2.5D finite-difference solution of the Helmholtz equation in the frequency domain (Abubakar et al., 2006). The algorithm employs a staggered-grid finite-difference solution to the total-electric-field Helmholtz equation in which the earth is defined as a 2D model (i.e. infinite in the strike direction), but with arbitrary source and receiver positions, which can therefore reflect the true acquisition geometry. In order to render the forward algorithm fast and efficient, several techniques have been implemented. The regions outside the domain of interest are discretized using optimal grids in both x and z directions. This helps to reduce the number of unknowns while still maintaining good accuracy. This optimal grid technique is also used to select the spatial frequency components along the invariant y-direction. Moreover, a material averaging formula (Keller, 1964) is used to calculate the effective material properties on both small and large grids. Finally, since the matrix generated from the finite-difference method is very sparse, a multi-frontal LU decomposition method is used as the solver, which can be very efficient for solving the electric field equation with multiple right-hand sides. The “structure”-based workflow can invert any parameter that describes the model, such as “structure” properties, any vertex or group of vertices in x, z or x and z directions. Another feature of the inversion is the use of the adjoint technique to calculate the Jacobian matrix. This technique significantly speeds up the inversion run time.

Examples

We illustrate the advantages and drawbacks of the “structure”-based inversion using both synthetic and real data. The real data were acquired during an extensive mCSEM program performed as part of a co-operation project between Petrobras and Schlumberger to evaluate mCSEM strengths and limitations when applied to the Brazilian deep offshore and to bring new insights toward the development of novel and cost effective solutions and establishment of new interpretation technology.

Details of the acquisition program are outlined in Zerilli et al. (2010). Figures 1-2 show the survey location and survey lay-out. Ten sail lines with receivers spaced approx. 1 to 2 km apart, were inverted using the actual survey acquisition parameters (8 frequencies from 1.75 to 0.0625 Hz) and instantaneous measurements of dipole length, dipole moment, dipole altitude, feather angle and dip. Selected receiver lines were inverted with the inline and a parallel broadside transmission for proper treatment of anisotropy.

Figure 3 shows the “structure”-based inversion results for the vertical resistivity of sail line LTAM08 across known reservoirs with the seismic image superimposed as well as the associated data misfit.

A detailed starting model was constructed based on interfaces identified from seismic interpretation and “background” resistivity distribution based on well log information and the results of an “image”-based inversion with the reservoirs boundaries fixed in x and z at the seismic interpretation locations (closed structures nodes) and only allowed horizontal and vertical resistivities to vary. The starting “closed structures” resistivities were set to the corresponding nearby “background” resistivities to allow them to become resistive as needed.

Figure 3 shows that the “structure”-based inversion is able to recover accurate reservoirs resistivities which are consistent with the available hard resistivity data.

Conclusions

We have presented a new mCSEM “structure”-based inversion capable of quantitatively reconstruct the resistivities and shapes of regions of interest such as prospective reservoirs based on *a priori* information to obtain models that are consistent with both the mCSEM and the seismic data. Considerable improvements in resolution can be achieved compared to the current state-of-the-art. We believe that this inversion coupled with development and refinement of mCSEM**,** new survey strategies and innovative integrated workflows with seismic, well log and production data could have a significant impact on: efficient appraisal of reservoirs, mapping of reservoir properties across the reservoir, monitoring of the changes in resistivity structure of a reservoir across its full lateral extent during production.

Acknowledgments

The authors thank Petrobras and Schlumberger for their support and willingness to share these results with the geophysical community. We also thank Vladimir Druskin and Mike Zaslavsky of Schlumberger Doll Research for helpful discussions on the forward algorithm.

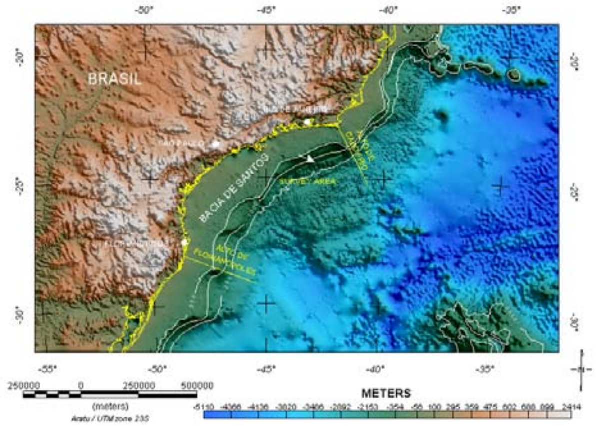

Figure 1. *Location of Survey Area*

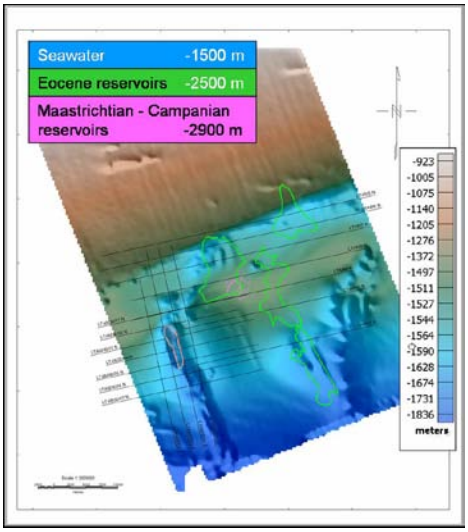

Figure 2. *Survey Area. mCSEM Sail lines*

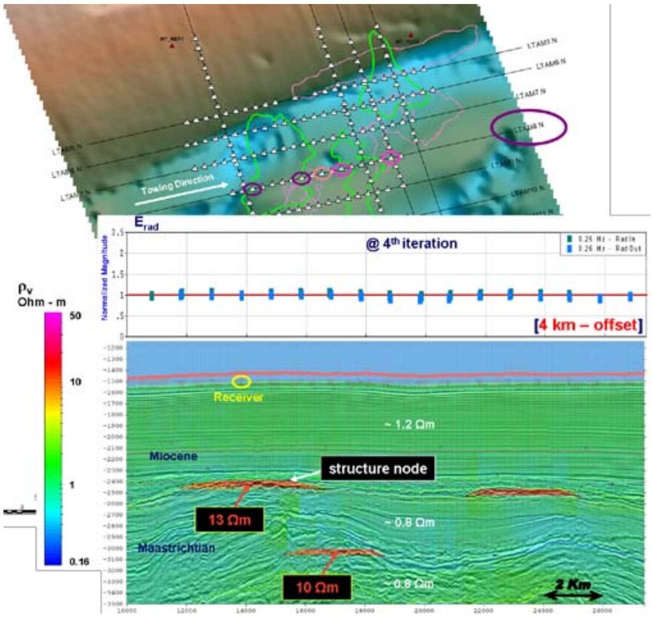

***Figure 3.** “Structure”-based inversion results of line LTAM08. Vertical resistivity depth section co-rendered with seismic. Seismic interpretation was used to structurally constrain the inversion. The image shows a consistent background resistivity trend and reveals resistivity anomalies (red) within the reservoirs boundaries fixed in x and z at the seismic interpretation locations (closed structures nodes). The upper graph shows normalized magnitude at 0.25 Hz and +/- 4 km offset to the final inversion model. The normalized graph shows that the data are well fit.*

References

Abubakar, A., Habashy, T.M., Druskin, V.L., Alumbaugh, D.L., Zerilli, A., Knizhnerman, L., 2006. Two-and-half-dimensional forward and inverse modeling for marine CSEM problems: *76th Ann. Int. Mtg., Soc. Expl. Geophys. Expanded Abstract,* 750-754.

Abubakar, A., T. M. Habashy, M. Li, and J. Liu, 2009. Inversion algorithms for large-scale geophysical electromagnetic measurements: *Inverse Problems*, 25, 123012.

Commer, M., and Newman, G., 2008. New advances in three-dimensional controlled source electromagnetic inversion: *Geophysical Journal International*, 172, 513–535.

Keller J.B., 1964. A Theorem on the Conductivity of a Composite Medium: *Journal Mathematical Physics,* 5, 548-549,

Habashy, T. M., Abubakar, A., 2004. A general framework for constraint minimization for the inversion of electromagnetic measurements: *Progress in Electromagnetic Research,* 46, 265–312.

Hesthammer, J.A., Stefatos, A., Boulaenko, M., Fanavoll, S., Danielsen, J., 2010. CSEM performance in light of well results: *The Leading Edge,* 29, no.1, 34-41.

Plessix, R. E., and W. A. Mulder, 2008. Resistivity imaging with controlled-source electromagnetic data: depth and data weighting: *Inverse Problem*, 24, 1–21.

Zerilli, A., Labruzzo, T., Buonora, M.P., Menezes, P.L., Rodrigues, L.F., Lovatini, A., 2010. 3D inversion of total field mCSEM data: The Santos Basin case study: *80th Ann. Int. Mtg., Soc. Expl. Geophys. Expanded Abstract,* 629-633.