Advanced 3D imaging of complex geoelectrical structures using towed streamer EM data

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Summary

The towed streamer EM system makes it possible to collect EM data with a high production rate and over very large survey areas. At the same time, 3D inversion of towed streamer EM data remains a very challenging problem because of the huge number of transmitter positions of the moving towed streamer EM system, and, correspondingly, the huge number of forward and inverse problems needed to be solved for every transmitter position over the large areas of the survey. We overcome this problem by exploiting the fact that a towed streamer EM system's sensitivity domain is significantly smaller than the area of the towed streamer EM survey. We have introduced the concept of a moving sensitivity domain, originally developed for airborne EM surveys, for interpretation of marine EM survey data as well, which makes it possible to invert the entire towed streamer EM surveys with no approximations into high-resolution 3D geoelectrical sea-bottom models. In order to improve the accuracy and reliability of the anisotropic 3D inversion results, we have developed 3D inversion method, which takes into account: 1) the variable background, 2) an a priori model constructed by anisotropic 1D inversion results, seismic data, and well-log data, and 3) bathymetry. We have applied our this method to the anisotropic 3D inversion of towed streamer EM data from the Mariner field in the North Sea. The results show that our method can recover a more reliable and reasonable 3D geoelectrical model, and the technology has proven to be fast and efficient for large amounts of towed streamer EM data in a complex geological setting.

Introduction

Marine controlled-source electromagnetic (MCSEM) methods are widely used for off-shore hydrocarbon (HC) exploration. It has been demonstrated in a number of publications that the adequate interpretation of MCSEM data requires taking into account the electrical anisotropy of the sea-bottom formations. In this paper, we demonstrate that our enhanced technology for the anisotropic 3D inversion makes it possible to produce clear images of sub-surface geoelectrical structure from the EM data collected by towed streamer EM system, which is capable of simultaneous seismic and EM data acquisition. The current generation of the towed streamer EM system consists of an electric bipole transmitter towed at a depth of 10 m below the sea surface, and up to a 9-km-long streamer of the electric field receivers towed at a depth of approximately 100 m.

The towed streamer EM system enables CSEM data to be acquired over very large areas in frontier and mature basins for higher production rates and more cost effective than conventional marine CSEM. At the same time, 3D inversion of the towed streamer EM data becomes a very challenging problem because the data are acquired over relatively large areas with a huge number of moving towed streamer EM system positions. We overcome this problem by exploiting the concept of the moving sensitivity domain (Zhdanov, 2010; Zhdanov and Cox, 2012; Zhdanov et al., 2014; Cox and Zhdanov, 2014), which is implemented using the integral equation (IE) method. In the framework of this concept, for a given transmitter-receiver pair, the responses and Fréchet derivatives are computed from a 3D earth model that encapsulates the towed EM system's sensitivity domain. The Fréchet matrix for the entire 3D earth model is then constructed as the superposition of Fréchet derivatives from all transmitter-receiver pairs over the entire 3D earth model. As a major vehicle of the regularized inversion, we use the Re-weighted Regularized Conjugate Gradient (RRCG) method (Zhdanov, 2002, 2009) with adaptive regularization in order to minimize the Tikhonov parametric functional.

In order to recover a reliable 3D geoelectrical model, the developed method of 3D anisotropic inversion takes into account: 1) a variable geoelectrical background, 2) an appropriate a priori model, and 3) the known bathymetry. The variable background, which can vary for different areas including both seawater and sea-bottom formations, helps extract more accurately the anomalous EM fields due to geoelectrical inhomogeneities, especially in the case of a large-scale survey. An appropriate a priori model can reduce the nonuniqueness of the inverse problem drastically. The bathymetry should be taken into account because it can distort the response of the sea-bottom formations.

We have applied this method to the anisotropic 3D inversion of towed streamer EM data acquired over the Mariner heavy oil field located in the UK North Sea, block 9/11a.

Inversion of the towed streamer EM data

The problem of inversion of geophysical data can be described as a solution of the corresponding operator equation:

$$\mathbf{d} = \mathbf{A}(\mathbf{m}),$$

where $\mathbf{A}$ is a nonlinear forward modeling operator, $\mathbf{m}$ is a tensor of the anomalous conductivities of the model determined on some discretization grid:

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$$\mathbf{m} = \Delta\hat{\boldsymbol{\sigma}} = \begin{bmatrix} \Delta\sigma_h & 0 & 0 \\ 0 & \Delta\sigma_h & 0 \\ 0 & 0 & \Delta\sigma_v \end{bmatrix},$$

and $\mathbf{d}$ stands for a data vector formed by the components of the observed EM field.

We use the integral equation (IE) method with variable background (Zhdanov, 2009) for solving the forward modeling problem, which is based on the following integral equation for an anisotropic medium:

$$\mathbf{E} = \iiint_D \hat{\mathbf{G}}_E \cdot (\Delta\hat{\boldsymbol{\sigma}} \cdot \mathbf{E}) dv + \mathbf{E}_b,$$

where $\mathbf{E}_b$ is the background electric field, and $\hat{\mathbf{G}}_E$ is a corresponding Green's tensor.

The inverse problem is ill-posed, i.e., the solution can be non-unique and unstable. The conventional way of solving ill-posed problems, according to regularization theory (Tikhonov and Arsenin, 1977; Zhdanov, 2002) is based on minimization of the Tikhonov parametric functional:

$$P^{\alpha}(\mathbf{m}) = \varphi(\mathbf{m}) + \alpha s(\mathbf{m}),$$

where $\varphi(\mathbf{m})$ is a misfit functional defined as a weighted norm of difference between the predicted and the observed data, $s(\mathbf{m})$ is a stabilizing functional, and α is a regularization parameter.

We solve the problem of minimization of the Tikhonov parametric functional using the re-weighted regularized conjugate gradient (RRCG) method with adaptive regularization parameter selection (Zhdanov, 2002). This method is based on iterative updates of the conductivity model $\mathbf{m}_n$ as shown in the following formulas:

$$\mathbf{r}_n = \mathbf{A}(\mathbf{m}_n) - \mathbf{d},$$

$$\mathbf{l}_n = \mathrm{Re}\mathbf{F}_n^* \mathbf{W}_d^* \mathbf{W}_d \mathbf{r}_n + \alpha \mathbf{W}_m^* \mathbf{W}_m (\mathbf{m}_n - \mathbf{m}_{apr}),$$

$$\beta_n = \|\mathbf{l}_n\|^2 / \|\mathbf{l}_{n-1}\|^2, \tilde{\mathbf{l}}_n = \mathbf{l}_n + \beta_n \tilde{\mathbf{l}}_{n-1}, \tilde{\mathbf{l}}_n = \mathbf{l}_0,$$

$$k_n = (\tilde{\mathbf{l}}_n, \mathbf{l}_n) / \left\{ \|\mathbf{W}_d \mathbf{F}_n \tilde{\mathbf{l}}_n\|^2 + \alpha \|\mathbf{W}_m \tilde{\mathbf{l}}_n\|^2 \right\},$$

$$\mathbf{m}_{n+1} = \mathbf{m}_n - k_n \tilde{\mathbf{l}}_n,$$

where k_n is a length of the iteration step; $\mathbf{W}_d$ and $\mathbf{W}_m$ are the data and model weighting matrices; $\mathbf{l}_n$ is the gradient direction, computed using the adjoint Fréchet derivative matrix, $\mathbf{F}_n^*$, and the star denotes the adjoint operator (matrix).

The Fréchet derivative is the most expensive item in the inversion not only in terms of the computation time, but also in the computer memory required for its storage. The number of entries in the Fréchet derivative matrix is equal to the number of data points times the number of cells in the inversion domain. With large amounts of data and vast inversion regions, the computer memory requirements may become prohibitive. To reduce the storage requirements, we use a moving sensitivity domain approach (Zhdanov and Cox, 2012; Zhdanov et al., 2014; Cox and Zhdanov, 2014) in our towed streamer EM data inversion.

Case Study – Mariner field

The Mariner field is located on the East Shetland Platform of the UK North Sea approximately 150 km east of the Shetland Isles (Figure 1). The Mariner oil field development entails investments of more than USD 7 billion and is the largest new offshore development in the UK in more than a decade. It is expected to start production in 2017. The field is estimated to produce for 30 years, with average production of around 55,000 barrels of oil per day over the plateau period from 2017 to 2020. The Mariner field consists of two shallow reservoirs, the Maureen Formation and the Heimdal Sandstones of the Lista Formation, with nearly 2 billion barrels of oil in place and expected reserves of more than 250 million barrels of oil. Both formations yield heavy oil of around 12 to 14 API. The field will be developed with a production, drilling and quarters (PDQ) platform, based on a steel jacket, with 50 active well slots, and floating storage unit (FSU) of 850,000 bbls capacity. In addition, a jack-up rig will be used for the first four to five years. Due to the low well flow rates and early water break-through, there is a need for many wells and a process designed to handle large liquid rates and oil-water emulsions. All production wells will have stand-alone sand screens and electric submersible pumps (ESPs) for lifting.

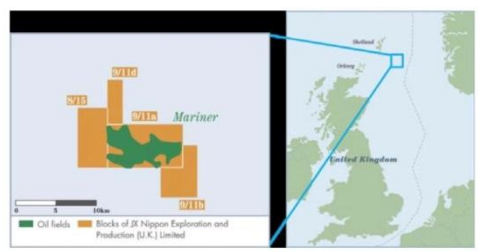

Figure 1: The location of the Mariner field in the North Sea.

The acquisition configuration and survey layout

The main features of the towed streamer EM configuration for the Mariner survey are shown in Figure 2. The bipole electric current source is 800 m long with a towing depth of 10 m. The source runs at 1500 A, and the source signal is a so-called Optimized Repeated Sequence (ORS) (Mattsson et al., 2012). In this case the useful frequencies range from 0.2 to 1.2 Hz with a step of 0.2 Hz. The signal sequence is 120 s long (one shot) with the source active during the first 100 s followed by 20 s of no signal, which is used for background noise estimation and noise reduction processing. The survey consisted of 10 lines separated by 500 m, as shown in Figure 3. The length of each line was about 15 km. Each line recorded 60 shots of 120 s lengths.

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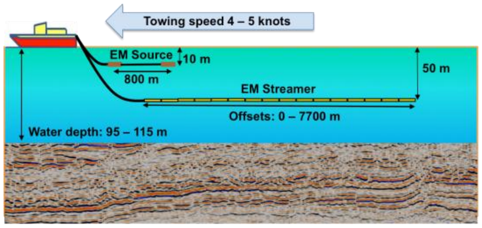

Figure 2: Geometry and towing configuration for the Mariner survey.

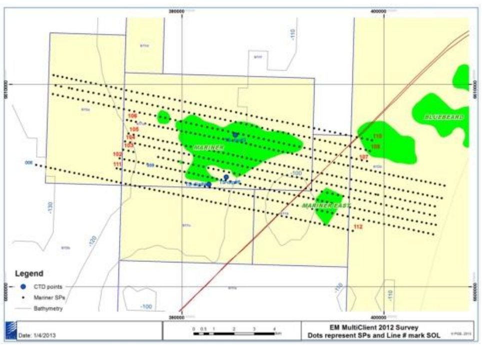

Figure 3: A map of the Mariner area showing the acquired lines and shot points.

3D anisotropic inversion of the towed streamer EM data

As demonstrated by Zhdanov et al. (2014), we expect that the use of a priori seismic and well-log information can reduce the nonuniqueness of the inverse problem and improve the resistivity image as well. The seismic and well-log information available in Mariner field were used to estimate the geometric structure, i.e., the horizons of the chalk layer on top of the basement as well as the depths and horizontal extents of the resistive region associated with the reservoirs, as shown in Figure 4. The chalk layer varies in depth below sea surface from 1400 to 1500 m with a basement underneath. The Maureen reservoir sits on top of the chalk, whereas the Heimdal reservoir is about 200 m above Maureen and the chalk. The bathymetry in the survey region varies between 95 and 115 m with a relatively homogeneous overburden.

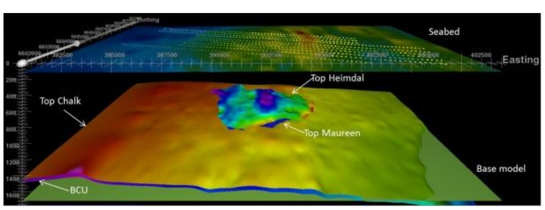

Figure 4: Seismic structure information showing the chalk layer and the two reservoirs close to the chalk.

In order to construct an appropriate 3D geoelectrical model which is used as the starting model in the anisotropic 3D inversion, we deployed anisotropic 1D inversion for each survey line. For all 1D inversions, the bathymetry in the survey area was taken into account, the response data at five frequencies from 0.2 to 1.0 Hz with 18 offsets ranging approximately from 1750 to 7450 m were used. The final a priori model was constructed using a 3D model from the results of 1D inversions geometrically constrained by seismic and well-log information.

In the anisotropic 3D inversion of the data collected from all the survey lines, the inversion domain was selected to cover all sensitive parts of the subsurface. The dimensions of the inversion domain were selected as follows: from -12000 m to 16000 m in the *x* direction; from -3600 m to 3600 m in the *y* direction; from 90 m to 3000 m in the *z* direction (positive downward). This rectangular region was discretized into cells of 50 m x 50 m x 25 m. The selected data for the inversion consisted of 323 shots with 18 offsets (approximately from 1750 m to 7450 m) and five frequencies (0.2, 0.4, 0.6, 0.8, and 1.0 Hz). The run time on a PC cluster with 16 cluster nodes, using 2.2 GHz Xenon Westmere processors running 4 OpenMP threads each, was about 17 hours.

Figure 5 shows an example of the observed and predicted data at a frequency of 0.2 Hz along a Line 105 presented as common mid-point (CMP) plots.

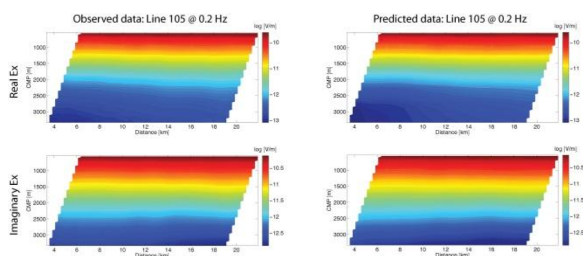

Figure 5: Observed (left panels) and predicted (right panels) data for in-line electric fields at 0.2 Hz along Line 105 presented as CMP plots.

The final model after 100 iterations in the anisotropic 3D inversion on all ten lines at the same time and with a resulting misfit of 5.4 % is shown in Figure 6 through 9. Figure 6 shows examples of the vertical cross sections of the 3D resistivity models along Line 105 recovered from the anisotropic 3D inversion. Figure 7 presents examples of the horizontal sections of the 3D resistivity models at a depth of 1425 m recovered from the anisotropic 3D inversion. Figures 8 and 9 show 3D perspective views of the 3D resistivity models recovered from the anisotropic 3D inversion of the towed streamer EM data for vertical and horizontal resistivities, respectively.

It can be seen that a resistive and anisotropic anomaly is showing up on top of a resistive chalk/basement

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underburden. This anomaly coincides well with the horizontal extent of the Heimdal and Maureen reservoirs even though this information was not exactly utilized in the anisotropic 3D inversion. Also, the recovered anisotropic feature in the reservoir volume agrees well with the known geoelectrical characteristics of Maureen and Heimdal reservoirs.

Conclusions

We have developed an advanced method of 3D inversion of the towed streamer EM data in order to improve the accuracy and reliability of the inversion results. The method takes into account all available a priori geological and geophysical information about the survey area. We applied this new technology to the anisotropic 3D inversion of the towed streamer EM data acquired over the Mariner field. It has been demonstrated that the recovered resistive and anisotropic anomaly volume agrees well with the structural knowledge of the Heimdal and Maureen reservoirs, with the known geoelectrical characteristics of the reservoirs, as well as the values for the underburden. The anisotropic 3D inversion and imaging of the data from the current generation of the towed streamer EM acquisition system can appropriately recover the anisotropic hydrocarbon-bearing formations. The developed inversion algorithm is based on the 3D contraction integral equation method with variable background, and the moving sensitivity domain approach. It has proven to be fast and efficient for a large towed streamer EM dataset in a complex geological setting.

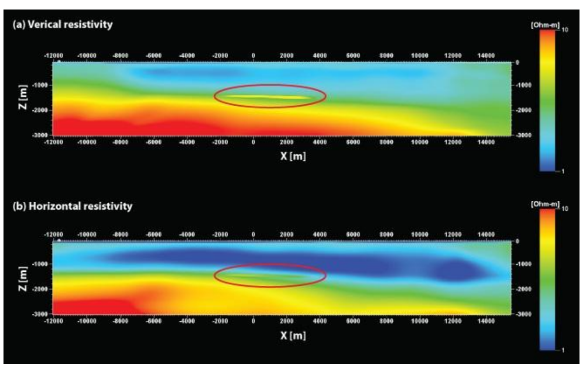

Figure 6: Vertical cross sections of the 3D resistivity distributions below survey line 105: (a) vertical resistivity, (b) horizontal resistivity, recovered from anisotropic 3D inversion. The reservoir locations are inside the red circles.

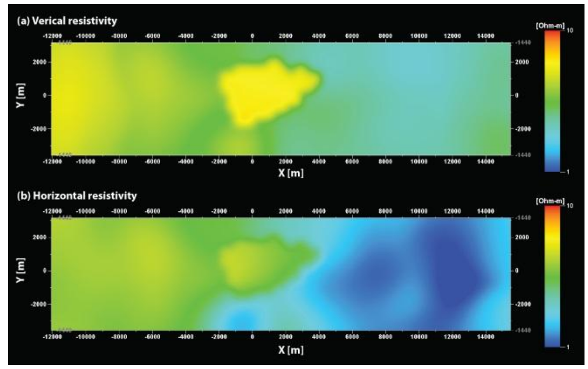

Figure 7: Horizontal sections of the 3D resistivity distributions at a depth of 1425 m: (a) vertical resistivity, (b) horizontal resistivity, recovered from anisotropic 3D inversion.

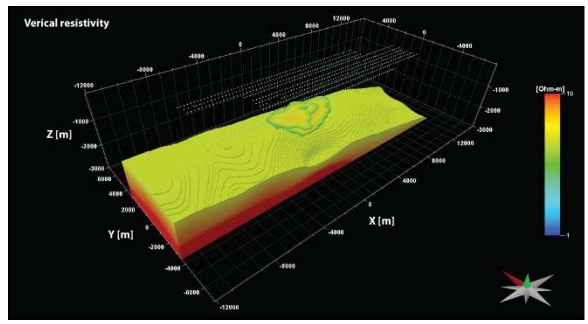

Figure 8: A 3D view of the 3D vertical resistivity distribution recovered from anisotropic 3D inversion.

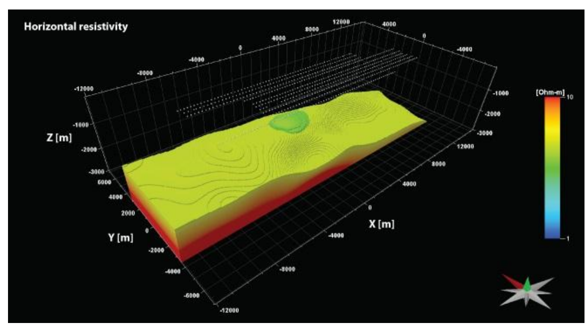

Figure 9: A 3D view of the 3D horizontal resistivity distribution recovered from anisotropic 3D inversion.

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EDITED REFERENCES

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