Integral Equation Method for Anisotropic Inversion of Towed Streamer EM Data - Theory and Application for the TWOP Survey

M. Zhdanov* (TechnoImaging and the University of Utah), M. Endo (TechnoImaging LLC), D. Yoon (TechnoImaging and the University of Utah), M. Cuma (TechnoImaging and the University of Utah), J. Mattsson (Petroleum Geo-Services) & J. Midgley (Petroleum Geo-Services)

SUMMARY

We introduce a 3D inversion methodology for towed streamer EM data that takes into account anisotropy and includes a moving sensitivity domain. Our implementation is based on 3D IE method for computing the responses and Fréchet derivatives, and uses re-weighted regularized conjugate gradient method for minimizing the objective functional with focusing regularization. Interpretation of the towed streamer EM data is a difficult problem because the data are acquired over large areas with huge number of moving towed streamer EM system positions. We overcome this problem by exploiting the concept of moving sensitivity domain, which is implemented using the 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. This makes large-scale 3D inversion a tractable problem with moderate cluster resources. We present a case study of 3D anisotropic inversion of towed streamer EM data from the Troll West Oil Province.

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 the MCSEM data requires taking into account the electrical anisotropy of the sea-bottom formations.

In this paper, we introduce a 3D anisotropic inversion methodology based on the integral equation method. We apply this method to the full 3D anisotropic inversion of the towed streamer Electromagnetic (EM) data. 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 the huge number of the moving towed streamer EM system positions. We overcome this problem by exploiting the concept of the moving sensitivity domain (Zhdanov and Cox, 2012; Zhdanov et al., 2013), which is implemented using the 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) with the vertical minimum support stabilizer, which helps to resolve relatively thin horizontal layers of the hydrocarbon (HC) reservoir.

We present a case study for the 3D anisotropic inversion of towed streamer EM data from the Troll field in the North Sea, and demonstrate our ability to image the Troll West Oil Province.

Inversion of the towed streamer EM data

The problem of geophysical data inversion is actually that of solving inverse operator equation:

$$\mathbf{d} = \mathbf{A}(\mathbf{m}), \tag{1}$$

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:

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

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

We use IE method for solving the forward modeling problem, which is based on the following integral equation for electric field $\mathbf{E}$ in anisotropic medium:

$$\mathbf{E} = \iiint_D \widehat{\mathbf{G}}_E \cdot (\hat{\boldsymbol{\sigma}} \cdot \mathbf{E}) dv + \mathbf{E}_b, \tag{2}$$

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

Inverse problem (1) is usually 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:

$$P^{\alpha}(\mathbf{m}) = \varphi(\mathbf{m}) + \alpha s(\mathbf{m}), \tag{3}$$

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

We introduce the minimum vertical support stabilizer, $s_{MVS}(\mathbf{m})$, which is proportional to the vertical size of nonzero values of the difference between the current model $\mathbf{m}$ and an appropriate a priori model $\mathbf{m}_{apr}$ in a horizontal section S (specially designed to invert for a thin, sub-horizontal structure typical for hydrocarbon reservoirs):

$$s_{MVS}(\mathbf{m}) = \iiint_V \frac{(m - m_{apr})^2}{\iint_S (m - m_{apr})^2 ds + \varepsilon^2} dv. \tag{4}$$

We solve the problem of minimization of Tikhonov parametric functional using the re-weighted regularized conjugate gradient (RRCG) method with adaptive regularization parameter selection (Zhdanov, 2002).

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., 2013) in our towed streamer EM data inversion.

Case study – Troll West Oil Province

The Troll Field is located in the Norwegian sector in the northern part of the North Sea. Water depths over the area range from 300 – 355 m. The Troll West Field was discovered in 1979 with production commencing in 1995. The Troll West oil province has a 22 – 26 m oil column under a small gas column. The Troll West gas province has a 12 – 14 m oil column under up to 200 m of gas. Oil is currently produced and a total of more than 110 horizontal production wells are planned including 28 multi-laterals. The gas will be produced after the oil is depleted.

The Troll East gas province was discovered in 1983. Gas production started in 1996 and approximately 2/3 of the recoverable gas will come from Troll East. Well descriptions indicate up to 110 m gas column. A small area in the northern part has a 6 – 9 m oil column that may turn out to be recoverable.

The field consists of three relatively large rotated fault blocks. The gas and oil in Troll East and West is found primarily in the Late Jurassic Sognefjord Formation, which consists of shallow marine sandstones. Part of the reservoir is also found in the underlying Middle Jurassic Fensfjord Formation consisting of 3 – 5 m coastal shallow marine sandstones arranged in several cycles. The seal is formed by Cretaceous and Paleocene claystones. Gas-filled reservoir intervals have resistivities of approximately 70 Ohm-m, while the water-saturated sands and overburden have resistivities in the range of 0.5 Ohm-m to 2 Ohm-m.

The TWGP is an ideal CSEM target, and has been previously surveyed for various conventional CSEM field trials (e.g., Amundsen et al., 2004; Gabrielsen et al., 2009). A field trial of the towed streamer EM system was undertaken over the Troll field during 2010 and 2012. The aim of these surveys was to demonstrate that the towed streamer EM system was capable of acquiring EM data suitable for delineating the Troll reservoir structures, and for extracting subsurface information about them via 3D inversion. Zhdanov et al. (2013) has successfully inverted the towed streamer EM data acquired over Troll field in 2010 for 3D isotropic geoelectrical model.

The Troll field trial in 2012 comprised of 12 lines of data acquired over TWOP above benign bathymetry at an acquisition speed of 4 knots, with an accumulated length of 180 km. The measured electric field is deconvolved with the output source current to obtain the frequency responses for all offsets and frequencies in the Optimized Repeated Sequences (ORS) at all shot points along the survey lines. The rate of production is typical for seismic acquisition, and is several times faster than conventional marine CSEM acquisition. The data were acquired in water depths of approximately 310 to 350 m, with the main reservoir at a depth of 1460 m. The reservoir below the mud-line has a 22 m to 26 m oil column under a small gas column. For this survey, 8700 m of long EM streamer was deployed with 23 receiver offsets between 500 m to 7500 m. The source operated at 1500 A with 800 m electrode spacing.

We applied our 3D anisotropic inversion with minimum vertical support regularization to the towed streamer EM data measured in 7 lines (lines 1 to 7; 11 offsets between 1860 and 7554 m) at 5 frequencies between 0.1 and 1.04 Hz with a priori geoelectrical model built using the seismic and well-log information available. Note that, the local coordinate system, converted from the global coordinate system, was used for the inversions, as shown in Figure 1. The 3D anisotropic earth model spanning the survey area was discretized to 250 m x 250 m x 50 m cells, from a depth of 400 m to a depth of 2400 m. The dimension of the inversion domain is: 32 km x 10 km x 2 km. The sediments were assigned a 2 Ohm-m isotropic resistivity. The L2 norm of the residuals between the observed and predicted EM data, normalized by the L2 norm of the observed data, converged to about 3.8 %. Figure 2 presents the example of the horizontal sections of the 3D resistivity models at a depth of 1475 m as recovered from the 3D anisotropic inversion with outlines of TWOP and TWGP known from geological data and drilling results. Figures 3 shows a 3D perspective view of the Troll reservoir model recovered from 3D anisotropic inversion of towed streamer EM data. As expected, one can see the TWOP and TWGP reservoirs as resistive structures in these images.

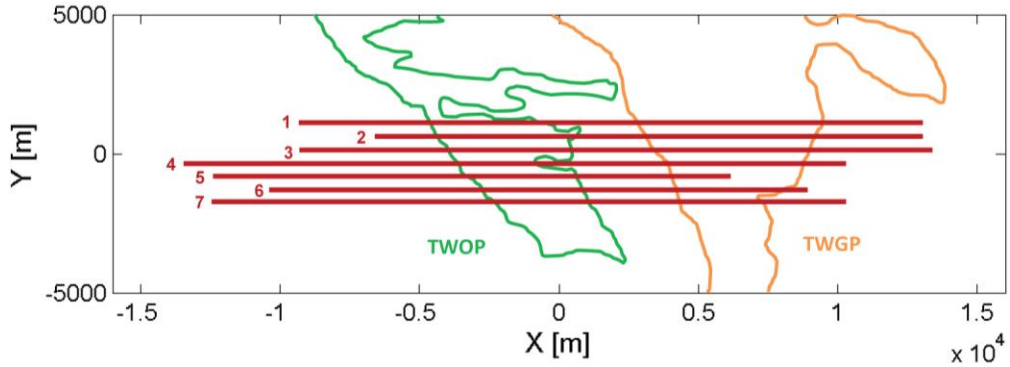

__Figure 1__ The survey configuration for 7-line towed streamer EM data inversion.

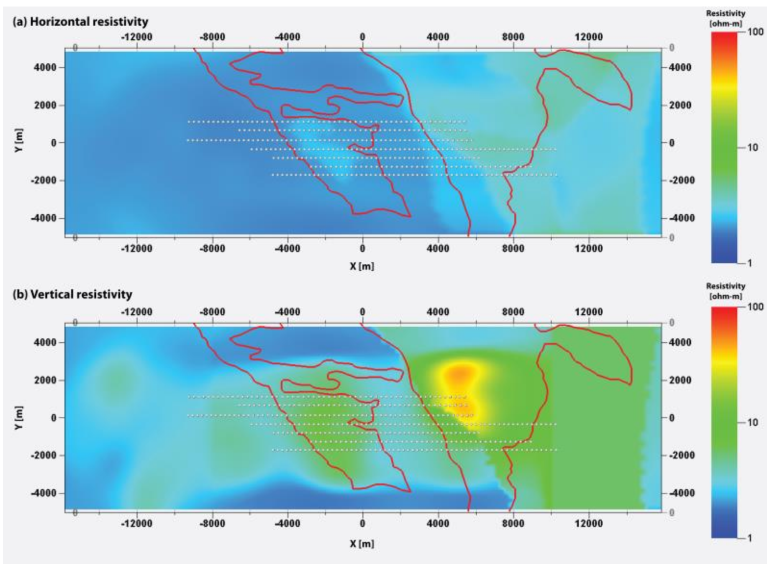

__Figure 2__ The horizontal section of the recovered by constrained inversion of 7-line data 3D horizontal (a) and vertical (b) resistivity distributions at a depth of 1475 m.

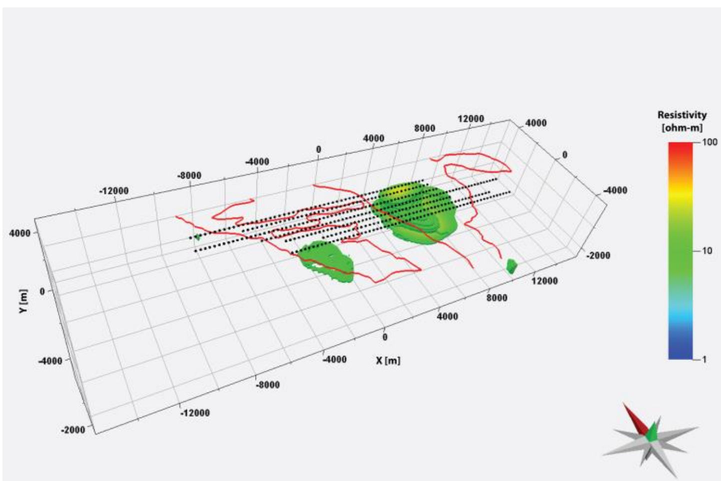

__Figure 3__ The 3D view of the recovered 3D vertical resistivity distribution (resistivity > 11 Ohm-m) by constrained inversion of 7-line data.

Conclusions

A towed streamer EM system capable of simultaneous seismic and EM data acquisition has recently been developed and tested in North Sea. The towed streamer EM system does not require the use of the fixed ocean bottom receivers and thus enables EM data to be acquired simultaneously with seismic data over very large areas in frontier and mature basins for higher production rates and relatively lower cost than conventional marine CSEM. We have developed an effective novel methodology for large-scale 3D anisotropic inversion of towed streamer EM data based on the integral equation method and moving sensitivity domain approach. We have also presented a case study of 3D anisotropic inversion of towed streamer EM data from a 2012 field trial over the Troll field in the Norwegian North Sea. We have demonstrated the ability of the method to image the Troll West Oil and Gas Provinces reservoirs from the towed streamer EM survey data. The towed streamer EM data were very high quality and regularized inversions converged successfully to 3D resistivity models that correlate well with the known structures of the Troll reservoirs. We conclude that, the 3D anisotropic inversion of the data from the current generation of towed streamer EM data acquisition systems can adequately recover the anisotropic hydrocarbon-bearing formations and that the developed methods provide a solid basis for continuous further developments of this new marine EM technology.

Acknowledgement

The authors acknowledge TechnoImaging, the University of Utah's Consortium for Electromagnetic Modeling and Inversion (CEMI), and Petroleum Geo-Services for support of this research and permission to publish.

References

Amundsen, H. E. F., S. Johansen, and T. Rosten, [2004], A sea bed logging (SBL) calibration survey over the Troll gas field: Presented at 66th EAGE Conference and Exhibition, Paris.

Gabrielsen, P. T., I. Brevik, R. Mitter, and L. O. Loseth, [2009], Investigating the exploration potential for 3D CSEM using a calibration survey over the Troll field: First Break, 27 (6), 67-75.

Tikhonov, A. N. and Y. V. Arsenin, [1977], Solution of Ill-posed Problems: Winston, New York.

Zhdanov, M. S., [2002], Geophysical Inverse Theory and Regularization Problems: Elsevier, Amsterdam.

Zhdanov, M. S., and L. Cox, [2012], Method of subsurface imaging using superposition of sensor sensitivities from geophysical data acquisition systems: US Patent Application No. US 2013/0173163.

Zhdanov, M. S., M. Endo, L. H. Cox, M. Cuma, J. Linfoot, C. Anderson, N. Black, and A. V. Gribenko, [2013], 3D inversion of towed streamer electromagnetic data: Geophysical Prospecting, in Press.