1D anisotropic inversion of marine CSEM data

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SUMMARY

When interpreting marine controlled-source electromagnetic (CSEM) data sets, it is often assumed that seafloor conductivity structures are electrically isotropic. However, it is commonly known that in the fold and thrust areas hydrocarbon reservoirs are frequently overlain by thick sedimentary sequences including shale and thinly interbedded sandstones. The effect of anisotropy on the marine CSEM responses needs to be addressed, and ignoring anisotropy in interpreting marine CSEM data may lead to a distorted image of seabed conductivity structures, even misinterpretation. In this paper, we present a one-dimensional anisotropic inversion method for frequency domain marine CSEM data sets. The partial derivatives of the electromagnetic fields with respect to both the anisotropic resistivity and thickness are analytically calculated. Both the synthetic and real data sets are inverted for demonstrating the practicality and stability of the presented inversion method.

Keywords: Marine CSEM, Anisotropy, Inversion, 1D, Resistivity

INTRODUCTION

The marine controlled-source electromagnetic (CSEM) method has emerged as a useful geophysical technique for offshore hydrocarbon reservoirs exploration and near-surface investigations. When interpreting marine CSEM data sets, it is often assumed that seafloor structures are electrically isotropic. However, it is commonly known that in the fold and thrust areas hydrocarbon reservoirs are frequently overlain by thick sedimentary sequences including shales and thinly interbedded sandstones. The sedimentary sequences and the thin banded sand-shale sequences can exhibit macroscopic electrical anisotropy. The effect of anisotropy on the marine CSEM responses needs to be addressed, and ignoring anisotropy in interpreting marine CSEM data may lead to a distorted image of seabed conductivity structures, even misinterpretation (Li and Dai, 2011, Li et al, 2012).

In this paper, we present a one-dimensional anisotropic inversion method for frequency domain marine CSEM data sets. The inversion approach is based on the Gauss-Newton scheme. The partial derivatives of the electromagnetic fields with respect to both the anisotropic resistivity and thickness are analytically calculated. An adaptive selection method of regularization factor, basing on the interrelation between the horizontal resistivity ($\rho_h$) and the vertical resistivity ($\rho_v$) of the inversion model, is proposed to balance the effects of the data misfit and the structural constraint. Both the synthetic and real data sets are inverted for testing the practicality and stability of the presented inversion method.

THEORY

Forward modeling

Due to the influence of ocean currents, the transmitter antenna will appear tilting and rotating. Applying superposition principle of electromagnetic field, we extend the scheme of Loseth and Ursin (2007) for calculating CSEM fields from a horizontal dipole source (HED) and/or a vertical dipole source (VED) in stratified media with vertical anisotropy to the general case of arbitrary orientation dipole source.

Gauss-Newton inversion method

The objective functional is given by

$$\phi(m) = \| W_d (d - F(m)) \|^2 + \mu \| W_m \nabla m \|^2$$

(1)

where $m$ is the model parameter vector, $\| \|_l^2$ represents the $l_2$ norm, $d = (d_1, \ldots, d_N)^T$ is the inversion data vector. $F(m)$ is the forward operator. $W_d$ is the data weighted matrix. $W_m$ is a diagonal weighting matrix penalizing the model parameter vector. The regularization parameter is selected as the product of the maximum row sum of the matrix product $[ (W_d J)^T (W_d J) ]$ and a weighting parameter (Newman et al., 1997)

$$\mu = \text{Max}_{i \in \Omega} \sum_{j=1}^{M} a_{ij} / \chi^{j+1}$$

(2)

where $a_{ij}$ is an element of the matrix $[(W_d J)^T (W_d J)]$ with $j = 1$ for the first iteration. $\chi$ denotes a cooling
parameter. \( \lambda \) is a weighting parameter of the inversion model. \( \mathbf{J} \) is the Jacobian matrix

\[
\mathbf{J}_i = \nabla_{\mathbf{m}} \mathbf{F}(\mathbf{m}_i) = \left( \frac{\partial \mathbf{F}(\mathbf{m}_i)}{\partial \log_{10} \rho} \right) \left( \frac{\partial \mathbf{F}(\mathbf{m}_i)}{\partial \log_{10} h} \right)
\]

The weighting vector \( \lambda \) consists of three parts: \( \lambda_h = 1 \) for the horizontal resistivity, \( \lambda_v \) (anisotropic ratio) for the vertical resistivity and \( \lambda_t = 1 \) for the thickness of each layer. The weighting parameter \( \lambda \) in the \( k \)-th iteration is given by

\[
\lambda_k = \begin{cases} 
\lambda_{h_k} = 1 & m \in \rho_h \\
\lambda_{v_k} = \sqrt{\frac{\rho_{v_k}}{\rho_{h_k}}} & m \in \rho_v \\
\lambda_{t_k} = 1 & m \in \text{thickness}(h)
\end{cases}
\]

where \( m \) is the model parameter and the initial value \( \lambda_i \) is set to be 1.

**MODELING**

**Sensitivity calculation**

To demonstrate the validity of the sensitivity computation procedure and the inversion code, we simulated the five-layer isotropic model displayed in Figure 1a. We evaluate the sensitivities with respect to \( \rho_h \) and \( \rho_v \) (assuming VTI-anisotropy), and with respect to isotropic \( \rho \). A line of 76 sources are placed 50m above the seafloor \((z=950m)\) and a receiver is located at the seafloor.

![Figure 1](image1.png)

**Figure 1.** 1D isotropic(a) and anisotropic(b) model.

![Figure 2](image2.png)

**Figure 2.** Comparison of sensitivities computed from the presented method and the isotropic algorithm (Li and Li, 2016). Frequency is 0.25 Hz. The left three columns show absolute values of sensitivity with respect to the horizontal, vertical and isotropic resistivity, respectively. The far right column shows relative errors between anisotropic and isotropic sensitivities.

For the isotropic model shown in Figure 1a, the isotropic sensitivities are the sums of the sensitivities with respect to both the horizontal and vertical resistivity (Streich et al., 2011). The left two
columns in Figure 2 show the sensitivity to the horizontal and vertical resistivity, respectively, computed by using the presented method. For comparison, the sensitivity computed from the code of (Li and Li, 2016) is shown in the third column, the relative differences are less than 0.3%.

Figure 3 shows the sensitivities of the horizontal resistivity (a) and vertical resistivity (b) of 1D anisotropic model shown in Figure 1b. One can see that the horizontal electric field is sensitive to the vertical resistivity of the reservoir layer. However, the sensitivity of horizontal electric field with respect to the horizontal resistivity of the reservoir layer is lower than that of both horizontal and vertical resistivities of the sediment layer and that of vertical resistivity of reservoir layer.

**Synthetic data inversion**

We present the inversion results of the synthetic horizontal electric and magnetic fields of the anisotropic model shown in Figure 1b. The signal is excited at 0.25Hz, 0.75Hz and 1.25Hz. 30 transmitters are spaced at 500m interval along the tow line at a height of 50m above the seafloor. A receiver is located at (0,0,0). The initial inversion model is an isotropic half-space of 1 Ωm.

Here we use an eigenparameter analysis method to demonstrate the resolution for multi-frequency data sets. The resistivity and depth of the seawater layer are fixed during the inversion. There are six unknown seafloor resistivities (ρ₁, ρ₂, ρ₃, ρ₄, ρ₅, ρ₆) and two unknown thickness of sediment layer and reservoir layer (h₁, h₂). The content of the Jacobian matrix J for the 1D model shown in Figure 1b is investigated by using a singular-value decomposition (SVD) to represent J as a product of three matrices (Inman et al., 1973)

$$J = USV^T$$

where U is a $N_d \times N_d$ matrix, $N_d$ and $N_m$ are the length of data vector and model parameter vector, respectively. The diagonal matrix S contains the eigenvalues (EVs) of J, and the matrix V contains the so-called eigenparameters (EPs).

Figure 4 shows the result of the eigenparameter statistical analysis for the 1D model inversion shown in Figure 1b. The white circles indicate positive components of EP, while the black circles indicate negative components. One can see that EP5 and EP6 (the vertical resistivity and thickness of the reservoir layer) are slightly coupled to each other, while the EPs corresponding the resistivities and the thickness of the sediment layer can be resolved independently, thus the resistivity of the reservoir layers could be recovered during the inversion.

**Figure 3.** Sensitivities of the horizontal resistivity (a) and vertical resistivity (b) of 1D anisotropic model shown in Figure 1b.

**Figure 4.** Eigenparameter statistical analysis of 1D anisotropic model shown in Figure 1b.

Figure 5a shows the inverted anisotropic seafloor resistivity. The final RMS misfit is 1.025. The dotted lines indicate the true resistivities and the star lines indicate the inversion results. From Figure 5a, one
can see that the horizontal and vertical resistivity of the surrounding sediments, and the vertical resistivity and the thickness of the thin resistive layer are reconstructed very well, but the horizontal resistivity of the thin resistive layer is badly recovered, which is insensitive known from the analysis of the sensitivities shown in Figure 3.

CONCLUSIONS

We present an anisotropic Gauss-Newton inversion method for frequency domain marine CSEM data. Both the synthetic and field data inversion examples indicate that the presented inversion method is stable and efficient.

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REFERENCES


