3D Anisotropic Inversion of Towed Streamer EM Data over the Mariner Field in the North Sea

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SUMMARY

Towed streamer electromagnetic (EM) data over the Mariner oilfield in the UK sector of the North has been inverted using a fast and efficient 3D anisotropic inversion code. The electric field data were acquired with a single vessel using a horizontal bipole source and sensors housed in a towed streamer in a densely sampled grid over the subsurface volume of interest. The inversion algorithm is based on the 3D contraction integral equation method and utilizing a re-weighted regularized conjugate gradient technique to minimize an objective functional. This inversion method is proven to be fast and efficient for large data sets and is here shown to be suitable for towed streamer EM data from complex geological environments such as the Mariner area. In this case, the final 3D resistivity cube after inversion and with a corresponding misfit of 6.4 %, agrees well with the expected structure from seismic data and well logs. In particular, the 3D cube contains a resistive anomaly of 8-10 Ωm corresponding to the Maureen and Heimdal reservoirs on top of the resistive chalk and basement.

Introduction

In this paper we present an anisotropic 3D inversion of towed streamer EM data acquired over the Mariner heavy oil field located in the UK North Sea block 9/11a. A dense grid EM survey (survey lines separated by 500 m) was acquired in order to estimate the resistivity structure in a volume including the Maureen and Heimdal reservoir structures in the Mariner complex.

We make use of a 3D anisotropic inversion methodology based on the integral equation method. This method is applied to the full 3D anisotropic inversion of the towed streamer electromagnetic (EM) data.

It is recognized that 3D inversion of the towed streamer EM data is a very challenging problem because of the huge number of the transmitter and receiver positions of the moving towed streamer EM system, and, correspondingly, a huge number of the 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. This approach has resulted in a paradigm change for towed streamer EM data interpretation by making it possible to invert entire towed streamer EM surveys with no approximations into high-resolution 3D resistivity sub seafloor models. This means that all reflection interactions in the resistivity structure as function of the wide frequency and offset bands are taken into account.
Our implementation of the inversion algorithm is based on the 3D contraction integral equation method for computing the EM responses and Fréchet derivatives, Portniaguine and Zhdanov (1999) and Zhdanov (2002), and uses the re-weighted regularized conjugate gradient (RRCG) technique (Zhdanov, 2002) for minimizing the objective functional with focusing regularization.

The acquisition configuration and survey layout

The main features of the towed streamer EM configuration for the Mariner survey are shown in Figure 1. The bi-pole electric current source is 800 m long with a towing depth of 10 m. The source runs at 1,500 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 Hz 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, Figure 2. The length of each line was about 15 km. Each line recorded 60 shots of 120 s lengths.

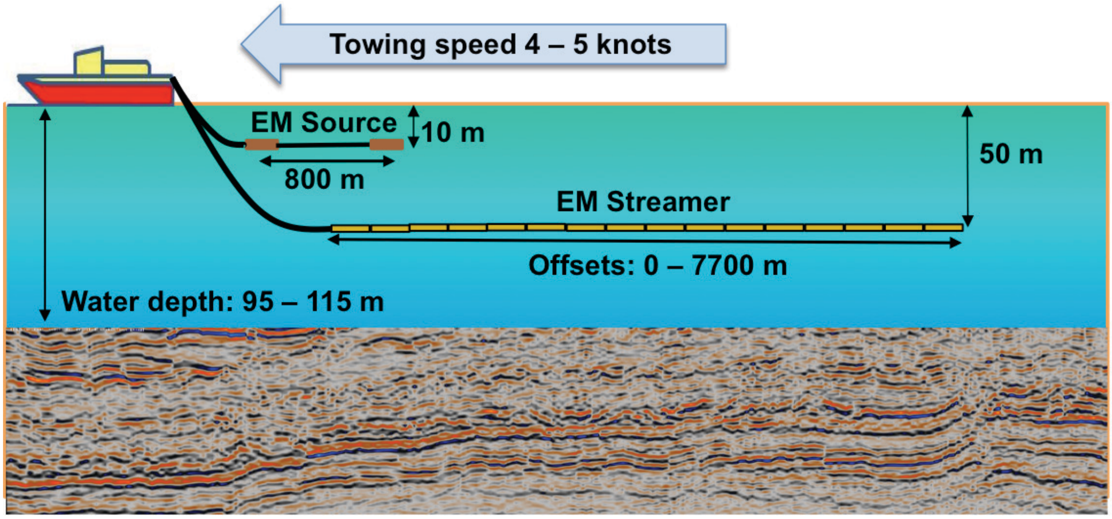

Figure 1 *The geometry and towing configuration at the Mariner survey.*

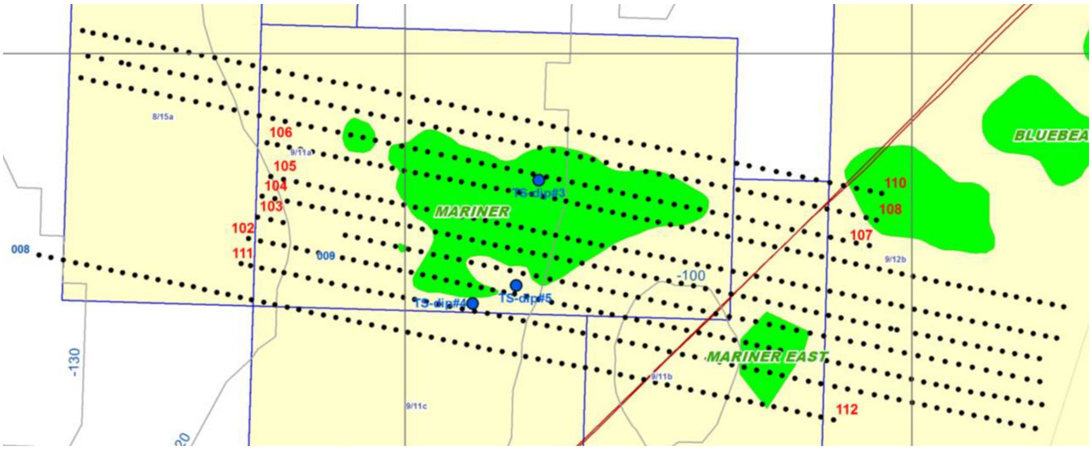

Figure 2 *A map of the Mariner area showing the acquired lines and shot points.*

The total uncertainty in the EM data

Estimating the uncertainty in the frequency response data as a function of signal is an important aspect of the processing and analysis of the acquired data. The uncertainty, originates from several sources including the measurement system, positioning errors, and the electric field noise in the measurement. The total uncertainty in the frequency responses is calculated for the data acquired in the grid over the Mariner area. The resulting average relative uncertainties in this data set are visualized in figure 3. The maximum relative uncertainty is seen to be below 5% in amplitude and below 2% in the phase. For most of the frequencies and offsets the uncertainties are below 1% in both the amplitude and phase. The dominant part of the uncertainty comes from the electric field noise for the low frequencies and long offsets. The sum of measurement and navigation uncertainties is below 1%.

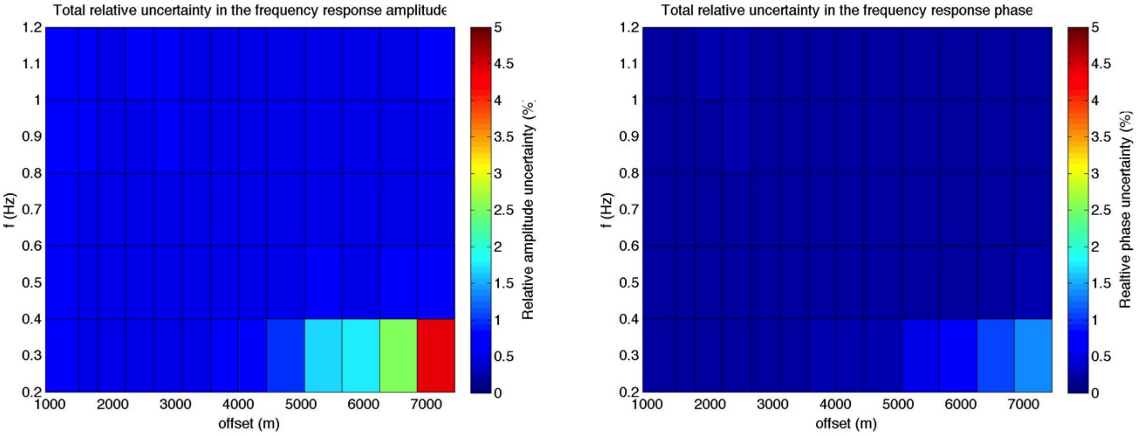

Figure 3 *The estimated total relative uncertainty in the frequency response amplitude (left) and phase (right) for one of the survey lines at the Mariner heavy oil field.*

The anisotropic 3D inversion

In order to establish some a priori structural information about the Mariner field, seismic data and well log data have been used to estimate the horizons of a chalk layer on top of basement as well as the depths and horizontal extents of the two resistive regions associated with the reservoirs Maureen and Heimdal, figure 4. The resistive chalk layer varies in depth below sea surface from 1400 to 1500 m with 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 region varies between 95 and 115 m with a relatively homogeneous overburden.

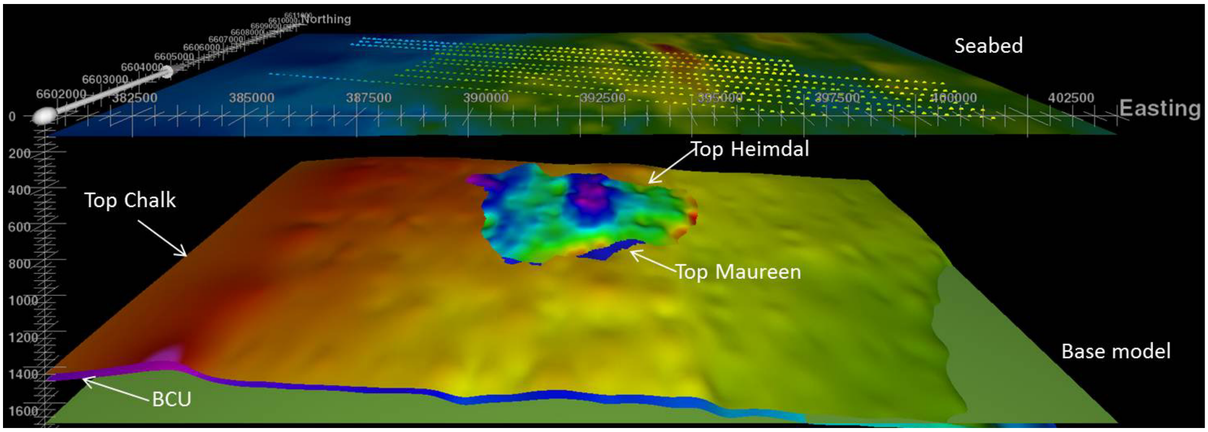

Figure 4 *A Seismic structure information showing the chalk layer and the two reservoirs close to the chalk.*

The 3D resistivity structure is estimated by minimizing the Tikhonov parametric functional:

$$P^{\alpha}(\Delta\sigma) = \left\| \mathbf{W}_d \left(\mathbf{A}(\Delta\sigma) - \mathbf{d} \right) \right\|_{L_2}^{2} + \alpha s(\Delta\sigma) \tag{1}$$

where **d** and **A(Δσ)** are the measured and modelled (**A** is a nonlinear forward modeling operator) electric field data, respectively. The data weights are denoted as $\mathbf{W}_d$. The regularization parameter α is updated in each iteration according to :

$$\alpha_n = \alpha_1 q^{n-1}; n = 1,2,3,\cdots; 0 < q < 1 \tag{2}$$

The stabilizing functional $s(\Delta\sigma)$ is in this case chosen as the minimum L2- norm of the difference between the current model and the a-priori model. The optimal step length q is determined to 0.75 from one-line anisotropic 3D inversions without any a-priori model (smooth inversion). A 1D background model of 2 Ωm is determined from 1D inversions.

The next step is to make use of the seismic structure in figure 4 to build an a-priori model to be used in the stabilizing functional. Since the chalk and the basement are resistive, this region below the top chalk horizon is set to 10 Ωm. The horizontal segment between the top chalk and the top Heimdal horizons is given a value of 3 Ωm whilst the remaining overburden is set to 2 Ωm. This a-priori model will guide the inversion result towards a more resistive underburden and with a hint that there is likely to be some higher resistive areas at the depths of the Maureen and Heimdal reservoirs.

The final model after 40 iterations in the 3D anisotropic inversion on all the ten lines at the same time and with a resulting misfit of 6.4 % is shown in figure 5. It can be seen that a high resistive anomaly of 8-10 Ωm is showing up on top of a high resistive chalk/basement underburden with resistivity up to 30 Ωm. This anomaly coincides well with the horizontal extent of the Heimdal and Maureen reservoirs even though this information has not been utilized in the inversion. However, the inversion has not been able to vertically split the anomaly into two separate parts corresponding to the vertical separation of the two reservoirs. The parts of the resistivity cube below 5 Ωm have been removed in the plots for visualization purposes.

The starting model in the 3D inversions is chosen as the background resistivity of 2 Ωm. In the final inversion with all survey lines the inversion domain selected to cover all sensitive parts of the subsurface. The dimensions are: X: from -18000 m to 18000 m; Y: from -6000 m to 6000 m; Z: from 200 m to 3000 m (positive downward). This rectangular region is discretized into cells of size 50 m x 50 m x 50 m. The selected data for the inversion consists of 323 shots with 16 offsets (1750 – 6700 m) and five frequencies (0.2, 0.4, 0.6, 0.8, and 1.0 Hz). The run time on a PC cluster with ten cluster nodes, using 2.2 GHz Xenon Westmere processors running 4 OpenMP threads each, was seven hours.

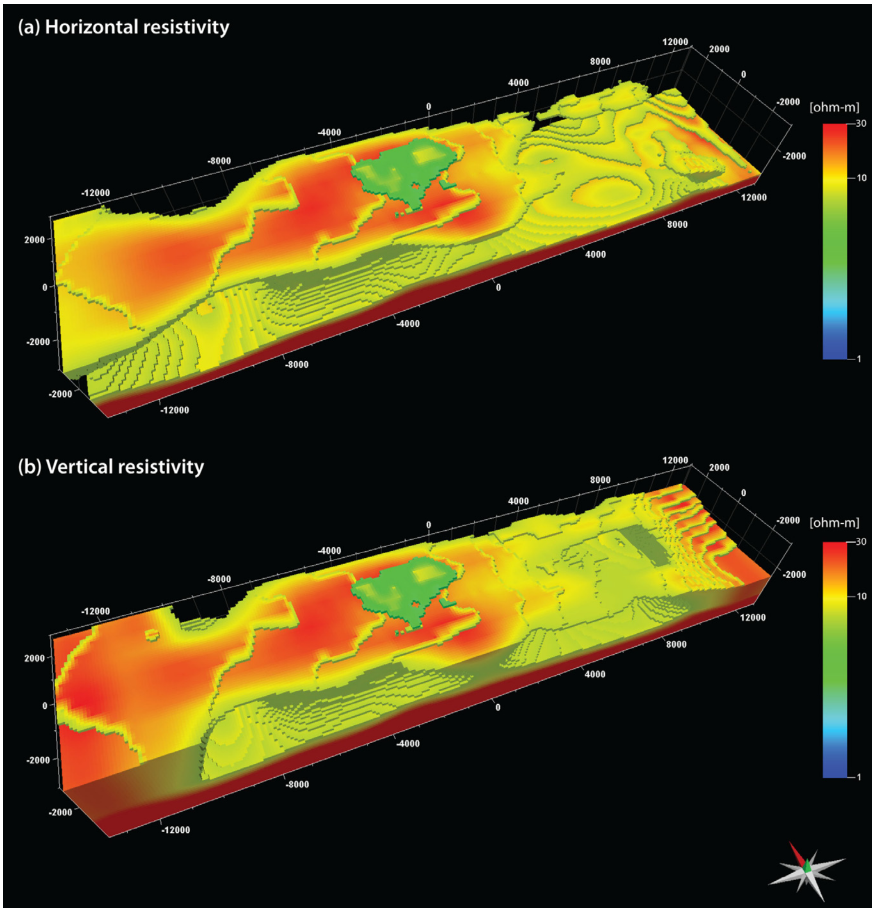

Figure 5 *The horizontal (top) and vertical (bottom) 3D resistivity cubes after inversion.*

Conclusions

The 3D anisotropic inversion of the Towed Streamer EM data acquired over the Mariner field results in a resistivity anomaly volume that agrees well with the horizontal structural knowledge of the Heimdal and Maureen reservoirs. The horizontal and vertical resistivity values in the anomaly corresponding with reservoirs are reasonable as well as the values for the underburden. The inversion algorithm based on the 3D contraction integral equation method and utilizing a re-weighted regularized conjugate gradient technique to minimize the objective functional, has proven to be fast and efficient for a relatively large towed streamer EM data set in a complex geological setting.

Acknowledgement

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