Advanced 3D imaging of complex geoelectrical structures using towed streamer EM data over the Mariner field in the North Sea

Michael S. Zhdanov[1,2*], Masashi Endo[1], David Sunwall[1] and Johan Mattsson[3] **present a case study for anisotropic 3D inversion of towed streamer EM data acquired over the Mariner heavy oil field.**

Towed streamer electromagnetic (EM) data acquired at the Mariner heavy oilfield in the UK sector of the North Sea have been inverted using a fast and efficient 3D anisotropic inversion code. The towed streamer EM system was towed from a single vessel. The system consisted of a horizontal bipole source and electrode sensors housed in a streamer cable. This enabled a densely sampled grid of data over the subsurface volume of interest. The purpose was to estimate the resistivity structure in a volume including the Maureen and Heimdal reservoir structures in the Mariner complex.

The 3D inversion algorithm is based on the contraction integral equation method and utilizes a re-weighted regularized conjugate gradient technique to minimize an objective functional (e.g., Zhdanov et al., 2014). A moving sensitivity domain approach is introduced to handle the large amount of data over the large area (Zhdanov, 2010; Zhdanov and Cox, 2012; Zhdanov et al., 2014; Cox and Zhdanov, 2014). This inversion method is proven to be fast and efficient 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 normalized misfit of 5.4% correlates well with the expected structure from seismic data and well logs. In particular, the 3D inversion was able to extract an anomaly with vertical and horizontal resistivities of 8-10 and 4-5 Ohm-m, respectively, corresponding to the Maureen and Heimdal reservoirs close to the resistive chalk and basement. The run time on a PC cluster was only seven hours for the full 3D inversion with data from all survey lines covering the area of interest.

The towed streamer EM system

The main features of the towed streamer EM configuration for the Mariner survey are shown in Figure 1. An 800 m long bi-pole electric current source is towed at a depth of 10 m where the electrodes are hanging underneath surface buoys with RGPS antennas. 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 a discrete set of frequencies ranging from 0.2 Hz to 1.2 Hz with a step of 0.2 Hz was used. The source sequence was 120 s long (one shot) with the source active during the first 100 s followed by 20 s of silence which was used for background noise estimation and noise reduction processing. The resulting electric field in the seawater was measured along the streamer cable as electric potential differences in distributed electrode pairs with offsets from 500 to 7700 m. In total, 72 electrode pairs of various lengths from 200 m in the front of the streamer to 1100 m at the end of the streamer were used in the configuration. The long electrode pairs reduce the towing and wave motion induced noise without loosing resolution in the sub-surface.

The Mariner field and the survey layout

The Mariner Field is located on the East Shetland Platform of the UK North Sea approximately 150 km east of the Shetland Islands (Figure 2). It consists of two shallow reservoirs 1200-1400 m below the sea surface, the Maureen Formation and the Heimdal Sandstones of the Lista Formation, with nearly

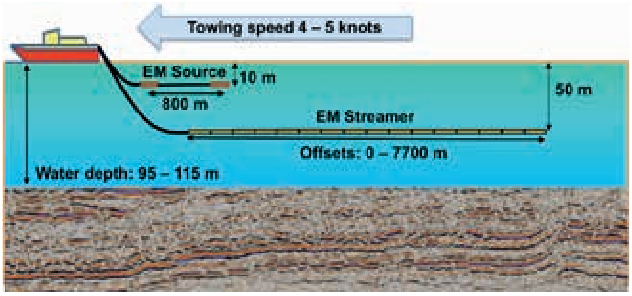

Figure 1 *The main features of the towed streamer EM configuration for the Mariner survey.*

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Figure 2 *The location of the Mariner field in the North Sea.*

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.

Seismic and well log data have been used to estimate the horizons of a chalk layer on top of basement as well as the horizons for the sandstones of the Maureen and Heimdal reservoirs (see Figure 3). 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 the Maureen reservoir and the chalk. The water depth in the region varies between 95 and 115 m with a relatively homogeneous overburden.

The survey consisted of ten lines separated by 500 m, as shown in Figure 4. The length of each line was about 15 km. Each line recorded 60 shots of 120 s lengths separated by 250 m with a towing speed of 4 knots.

Anisotropic 3D inversion

The 3D resistivity structure is estimated by minimizing a Tikhonov parametric functional with respect to the horizontal and vertical horizontal conductivity change $\Delta \sigma$ from a background model (Zhdanov, 2002). At each inversion iteration, computation of the sensitivities for an entire towed streamer EM survey is needed. We use quasi-Born approximation (Zhdanov, 2009), which reduces the amount of computation dramatically while retaining a numerically stable solution. The number of entries in the sensitivity matrix is equal to the number of towed streamer EM data points times the number of cells in the inversion domain, which can be large. To reduce the storage requirements, we limit the sensitivity to a moving sensitivity domain around

Figure 3 *Seismic structure information showing the chalk layer and the two reservoirs close to the chalk.*

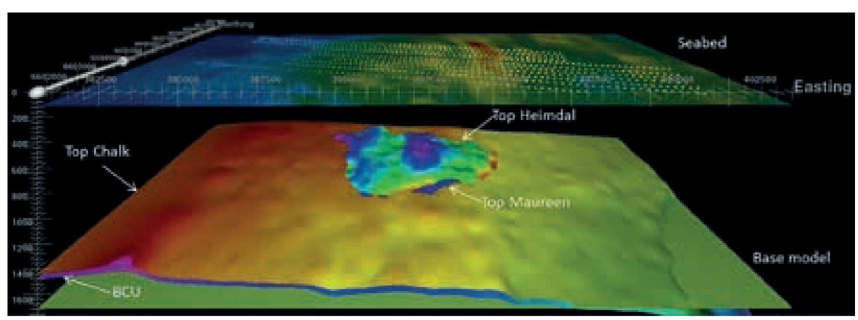
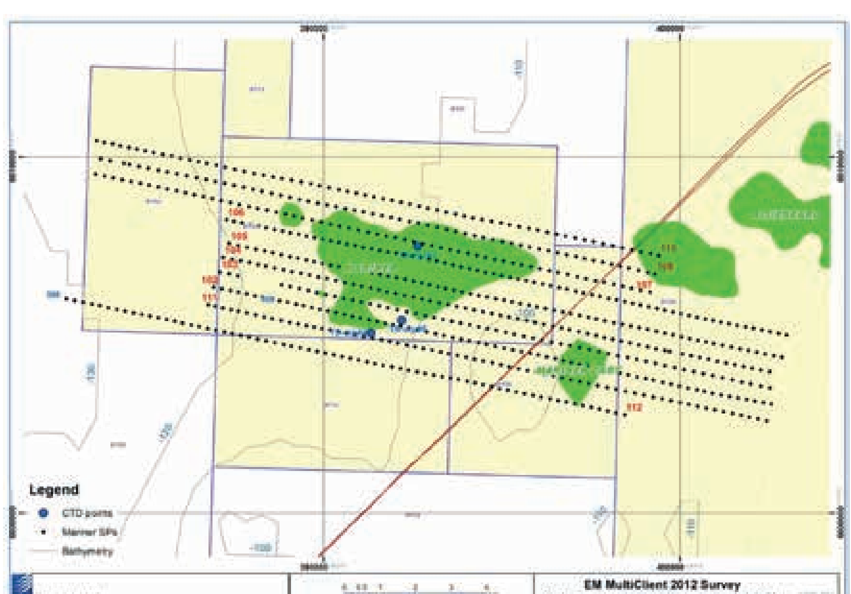


Figure 4 *A map of the Mariner area showing the acquired lines and shot points.*



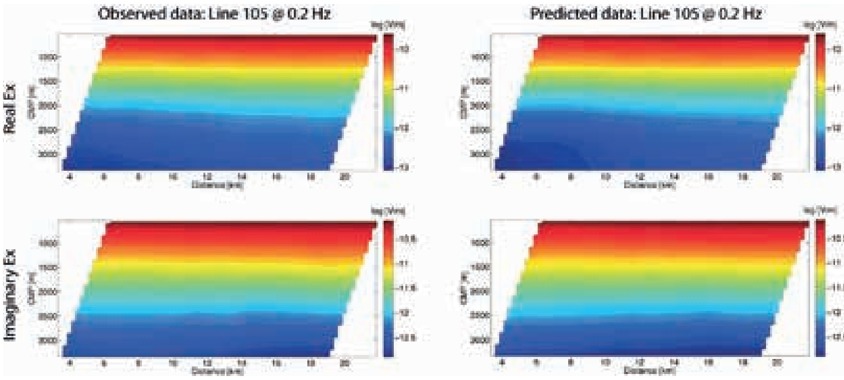


Figure 5 *Observed (left panels) and predicted (right panels) data for in-line electric fields at 0.2 Hz along Line 105 presented as CMP plots.*

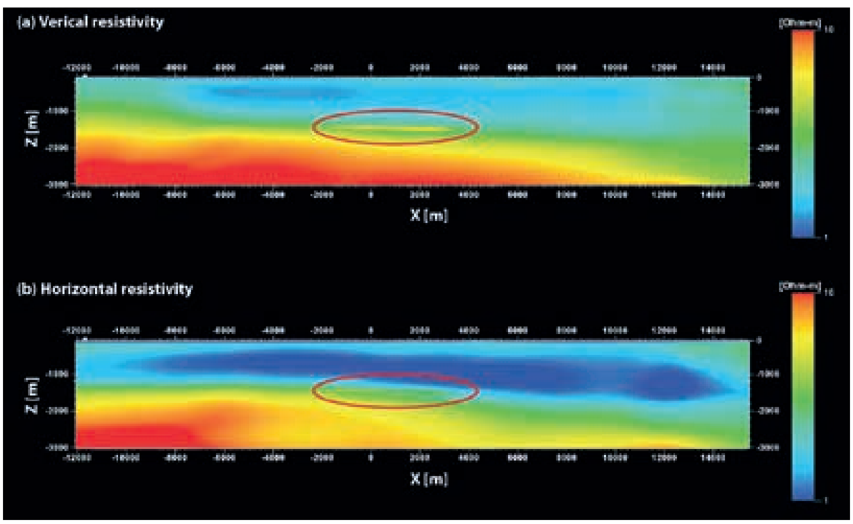


Figure 6 *Vertical cross-sections of the 3D resistivity distributions below survey line 105: (a) vertical resistivity, (b) horizontal resistivity, recovered from anisotropic 3D inversion. The reservoir locations are inside the red circles.*

each transmitter-receiver pair (Cox et al., 2010) by using only sensitivity inside the inversion cells within a predetermined horizontal distance from this transmitter-receiver pair only. The size of the moving sensitivity domain is determined by the rate of sensitivity attenuation of towed streamer EM data.

Our large-scale dense 3D towed streamer EM data inversion uses two levels of MPI parallelization, the higher level over the transmitters (sources), and the lower level over the horizontal layers of the discretization grid. Furthermore, each MPI process launches multiple OpenMP threads. On our cluster computers, we typically map one MPI process per CPU socket and associate threads with CPU cores.

In order to determine the optimal parameters of the inversion and a general background geoelectrical model, we first run the anisotropic 3D inversions without any a-priori model (unconstrained inversion). It is well-known, however, that the use of a priori seismic and well-log information can reduce the non-uniqueness of the inverse problem and improve the resistivity image significantly. The high spatial data density also reduces the non-uniqueness compared to a more sparsely sampled data set. The seismic and well-log information available for the 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 (see Figure 3). The chalk layer varies in depth below the 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. Since the chalk and the basement are resistive, this region below the top chalk horizon is set to 10 Ohm-m in the a-priori model. The horizontal segment between the top chalk and the top Heimdal horizons is given a value of 3 Ohm-m, while the remaining overburden is set to 2 Ohm-m. The bathymetry in the survey region varies between 95 and 115 m with a relatively homogeneous overburden.

This information was used for constructing the a priori model for the seismically guided/constrained inversion. 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. It is not a hard constraint with the horizons as boundaries. All resistivity values are still free to take any values to minimize the parametric functional.

The a-priori model only guides the solution towards a more geologically plausible model. The dimensions of the inversion domain were selected as follows: from -12,000 m to 16,000 m in the x direction (parallel to the survey lines); from -3600 m to 3600 m in the y direction (perpendicular to the survey lines); 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

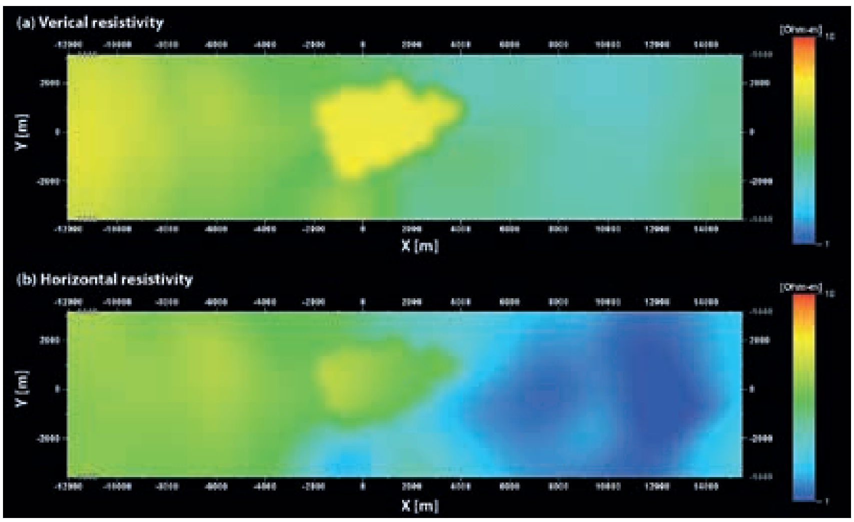


Figure 7 Horizontal sections of the 3D resistivity distributions at a depth of 1425 m: (a) vertical resistivity, (b) horizontal resistivity, recovered from anisotropic 3D inversion.

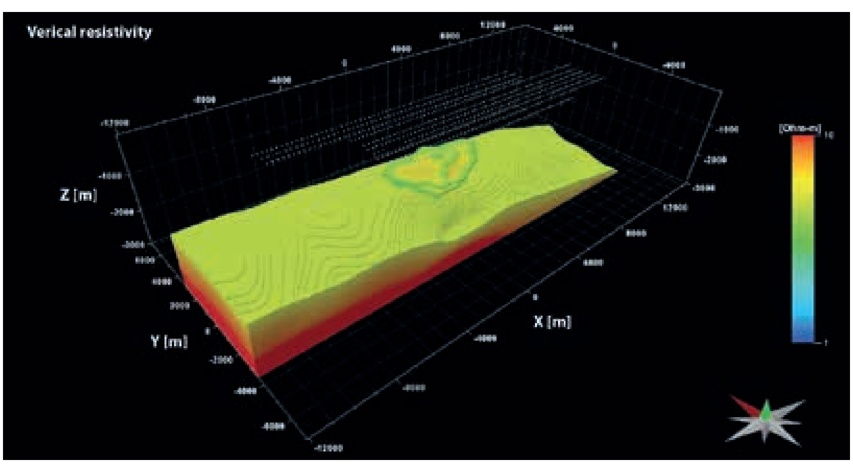


Figure 8 A 3D view of the 3D vertical resistivity distribution recovered from anisotropic 3D inversion.

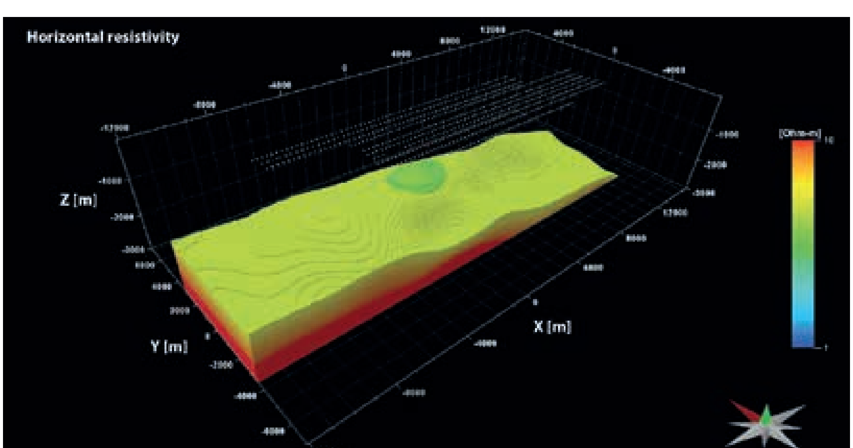


Figure 9 A 3D view of the 3D horizontal resistivity distribution recovered from anisotropic 3D inversion.

(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 four OpenMP threads each, was about seven hours.

Figure 5 shows an example of the observed and predicted data at a frequency of 0.2 Hz along Line 105, Figure 4, presented as common mid-point (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 below the sea surface 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 is clearly seen that the resistive anomaly appears right on top of the chalk, which corresponds with the Maureen and Heimdal in depth. The anomaly also coincides with the horizontal extent of the Heimdal and Maureen reservoirs even though this information has not been utilized in the inversion. The anomaly is even more visible in the cross section anisotropy plot where the isotropic chalk/basement disappears leaving the reservoir anomaly with a clear anisotropy i.e. the square root of the ratio between the vertical and horizontal resistivities of approximately 1.5. It should be emphasized that the high spatial density of the EM data makes it possible to extract the resistive anomaly corresponding with Maureen and Heimdal even though they are close to the chalk/basement layer with higher resistivity from the 3D 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.

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