Three-Dimensional Inversion of Troll West Oil Province EM Data Acquired by a Towed Streamer EM System 2012

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SUMMARY

In October 2012, several of previously known oil and gas fields, located in the North Sea, were surveyed with the newly developed Towed Streamer EM System. This paper discusses a first result of a three dimensional inversion of a subset of the data acquired over Troll West Oil Province (TWOP). The TWOP field is located in the Norwegian sector of the northern part of the North Sea. The water depths over the area range from 310 m to 350 m. The reservoir at a burial depth of 1150 m below the mud-line. The inversion of the Towed Streamer EM System-data acquired over TWOP results in a resistivity anomaly volume that agrees well with the horizontal extent of the target response data and in a correct burial depth from a priori information. Moreover, it also agrees well with previous results from node system data. The result required less than 20 minutes on a 16 processor computer.

Introduction

In October 2012, several of previously known oil and gas fields, located in the North Sea, were surveyed with the newly developed Towed Streamer EM System. This paper discusses a first result of a three dimensional inversion of a subset of the data acquired over Troll West Oil Province (TWOP). The first two sections briefly describe the Towed Streamer EM system and the acquisition area. The third section describe, on a formal level, the theory applied and finally, the last section discusses the numerical result.

The Troll West Oil Province field is located in the Norwegian sector of the northern part of the North Sea. The water depths over the area range from 310 m to 350 m. The reservoir at a burial depth of 1150 m below the mud-line has a 22 m – 26 m oil column under a small gas column. The electrical resistivity in the reservoir is about 10 Ωm to 15 Ωm. The horizontal extent is roughly 3 × 8 km and the over and under burden are relatively homogeneous and consists of shale. The vertical resistivity is about 3 Ωm and horizontal resistivity about 1.5 Ωm.

Towed Streamer EM System

The Towed Streamer EM system consisted of a surface towed source 10 m below the surface, and with a source strength of 1.2 MAm. From the same vessel an 8700 m long EM streamer was towed at a depth of 100m. In Figure 1 the corresponding layout is illustrated. The injected electric current from the source was transmitted as an Optimized Repeated Sequences (ORS), where each sequence consisted of a 100 s long active part (source on) followed by a 20 s silent period (source off). The resulting electric field was measured along the streamer at effectively 23 offsets ranging from 500 m to 7500 m at a towing speed of 4 kn. The silent periods are used for noise estimation and noise reduction processing. The source sequence was designed to obtain as high energy as possible in a discrete set of frequencies where the electric field response is sensitive to the resistive reservoir anomaly. See Mattsson et al. (2012) for a presentation of the deconvolution and current noise reduction methodology for the Towed Streamer EM System.

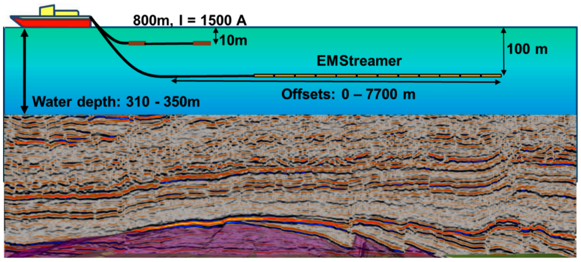

Figure 1: The Towed EM System at its maximum towing depth.

Integrated target response

In total 12 lines were shot over TWOP with an accumulated length of 180 km. The measured electric field is deconvolved with the output source current to obtain the frequency (earth) responses for all offsets and frequencies in the ORS sequence at all shot points along the survey lines. The changes in the frequency responses caused by resistivity and bathymetry variations may sometimes effectively be visualized as a target response data attribute (normalized frequency responses). In this case an integrated target response is calculated at the frequency 0.248 Hz for offsets between 5100 and 7600 m at each common mid-point (cmp) position. The frequency responses are normalized with one of the frequency responses at a cmp between TWOP and the Troll West Gas Province (TWGP) east of TWOP and then summed over the selected offset range. The result for the seven survey lines used in the 3D inversion below is shown in Figure 2 where the amplitude of the integrated target response is plotted to the left in a color scale on top of the cmps. The phase is plotted in the same way to the right. A seismic outline of TWOP is drawn in black.

The effect from TWGP is seen as the dark red colored parts to the east in the amplitude and phase plots in Figure 2. The TWOP shows up in the south area within the black outline. The red is a strong response while the blue is no response. The location of both the amplitude and phase responses associated with the TWOP agrees well with the inversion results in Zach et al. (2009) and with the horizontal extent of the 3D inversion result below. Towards the south-west end, there is a response that is seen in all offsets and frequencies which indicates that it is caused by something very shallow, most likely a bathymetry

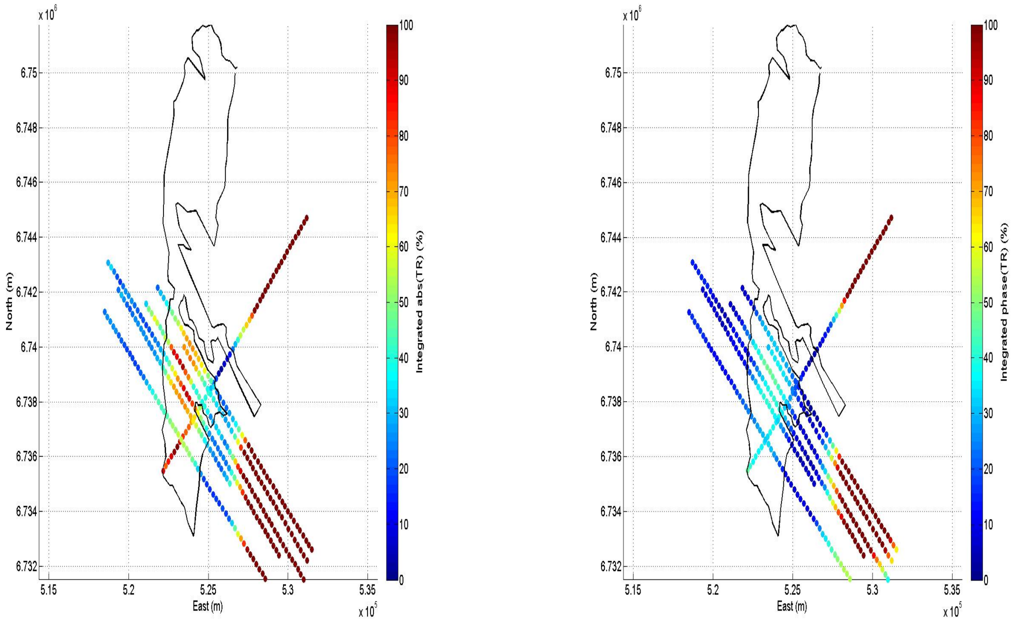

Figure 2: The survey lines over TWOP for the 3D inversion. The color coding represents the integrated target response data attribute with relative magnitude change to the left and relative phase change to the right.

effect. In fact the water depth decreases to 250 m in this area. There is also a bathymetry decrease to the north-west, which is also visible in the target response data. In contrast, the response associated with the TWOP is seen only for the longest offsets (5100 m – 7600 m) and the lowest frequencies (0.1 Hz – 0.5 Hz). Hence, the anomaly cannot be caused by something shallow.

3D inversion theory

We will now briefly and formally, discuss the theory. This section only provide the theory on a somewhat abstract level, and the particular choices and motivation will be done in the next section. We assume the background to be described by horizontally stratified sections, representing the physical properties of conductivity and the permittivity, characterized by a finite frequency dependent family, $\{\gamma_n\}_{n=1}^{N}$, of operators defined by

$$\gamma_n := \begin{bmatrix} \gamma_n^{\mathrm{H}} & 0 & 0 \\ 0 & \gamma_n^{\mathrm{H}} & 0 \\ 0 & 0 & \gamma_n^{\mathrm{V}} \end{bmatrix},$$

with complex elements. The background constructed from this family is referred to as γ. We formulate the theory with respect to one fixed frequency, f. The version of Maxwells equations that governs the propagation of $\{\mathbf{E},\mathbf{H}\}$, the electric and magnetic vector fields, are:

$$\mathbf{M}\begin{bmatrix} \mathbf{E} \\ \mathbf{H} \end{bmatrix} = \begin{bmatrix} \mathbf{j} \\ \mathbf{0} \end{bmatrix},$$

where

$$\mathbf{M} := \begin{bmatrix} \gamma\mathbf{I} & \mathbf{curl} \\ \mathbf{curl} & -i\mu 2\pi f\mathbf{I} \end{bmatrix},$$

and j represent the source discussed in the previous section. Here μ is the magnetic permeability.

We assume appropriate boundary conditions and radiation properties and calculate the Greens tensor $\mathbf{G}$ for the associated electric field and the background field $\mathbf{E}^b$. We represent any deviation from this background by a new operator $\Delta\gamma$, which in general will have compactly supported elements. Thus in the presence of any deviation, the electric field **E**, that we measure, will be controlled by the following inhomogeneous Fredholm equation of the second kind:

$$\mathbf{E}(\mathbf{x}) = \mathbf{E}^b(\mathbf{x}) + \int \mathbf{G}(\mathbf{x},\mathbf{x}')\Delta\gamma(\mathbf{x}')\mathbf{E}(\mathbf{x}')\mathrm{d}\mathbf{x}'.$$

If we write the solution to this equation as $\mathbf{E}_{\Delta\gamma}$, the inversion is conducted by finding a certain local minima to

$$\|\mathbf{E}_{\Delta\gamma} - \mathbf{d}\|^2_{\mathscr{D}} + \mathscr{E}(\Delta\gamma),$$

restricted to a set $\mathscr{B}$. Here the norm $\|\cdot\|_{\mathscr{D}}$ represents the norm used for the data, $\mathscr{E}(\cdot)$ a mapping associated with the model, and $\mathscr{B}$ represent a set of what we consider to be feasible solutions. The data is represented by **d**.

Results

For the inversion, using the TWOP-data, we select a subset according to Table 1. The target was most sensitive to the frequency 0.248 Hz at mainly longer offsets. To cover the frequency range we are sensitive to we choose two additional frequencies, see Table 1.

Data from Lines	1, 2, 3, 4, 5, 7, 14
Frequencies [Hz]	0.148, 0.248, 0.347
Offsets [m]	4554, 5152, 5751, 6350, 6949, 7548

Table 1: Data for the TWOP-inversion.

The particular mid-points, shown in Figure 3, were chosen so that we would have what we considered to be sufficient coverage of data. To be able to conclude that the background can be approximated by horizontally stratified sections we did a one-dimensional inversion based on the trust region algorithm from Coleman and Li (1996) to derive the family, characterizing the background, discussed in the previous section. The best result was over Line 5, with a water depth 318 m followed by a sediment layer interface at 1046 m. The associated resistivity was measured to 0.267 Ωm in the water. In the first sediment the vertical resistvity is 2.77 Ωm and the horizontal resistivity is 1.610 Ωm. In the second sediment the vertical resistivity is 3.152 Ωm and the horizontal resistivity is 1.150 Ωm.

The particular weights introduced in the previous section are based on the one in Gribenko and Zhdanov (2007) for balancing the dynamic range present in the data. The model weights are based on a combination of weights that can be found in e.g. Zhdanov (2002) which focus on maintaining a somewhat more neutral impact from all of the inversion parameters along with that the model should be, in some sense, concentrated. Finally the feasible set will contain physically realistic isotropic models. We would stress that no Sobolev type norm was used. We could have used metrics that focused the inversion more, but we choose not to use that since the data did not provide us with such a information. This explain why our result is a bit less focused compared to other results on this case. The inversion algorithm is basically a Gauss-Newton method (the second order derivative is approximated in the usual way) with a line search suggested in Abubakar et al. (2008). The anomaly, described as a deviation in the previous section, is approximated by simple stepwise constant functions. Our starting model was simply our background model and this was also our reference model. No additional work was needed. Our final model can be found in Figure 3, with a resulting target depth, measured from the sea surface, at 1450 m, a maximum resistivity of 11 Ωm, and a thickness of approximately 30 m. This model agrees, under our assumptions, quite well with previous knowledge see e.g. Zach et al. (2009).

Conclusions

The inversion of the Towed Streamer EM System data acquired over TWOP results in a resistivity anomaly volume that agrees well with the horizontal extent of the target response data and in a correct

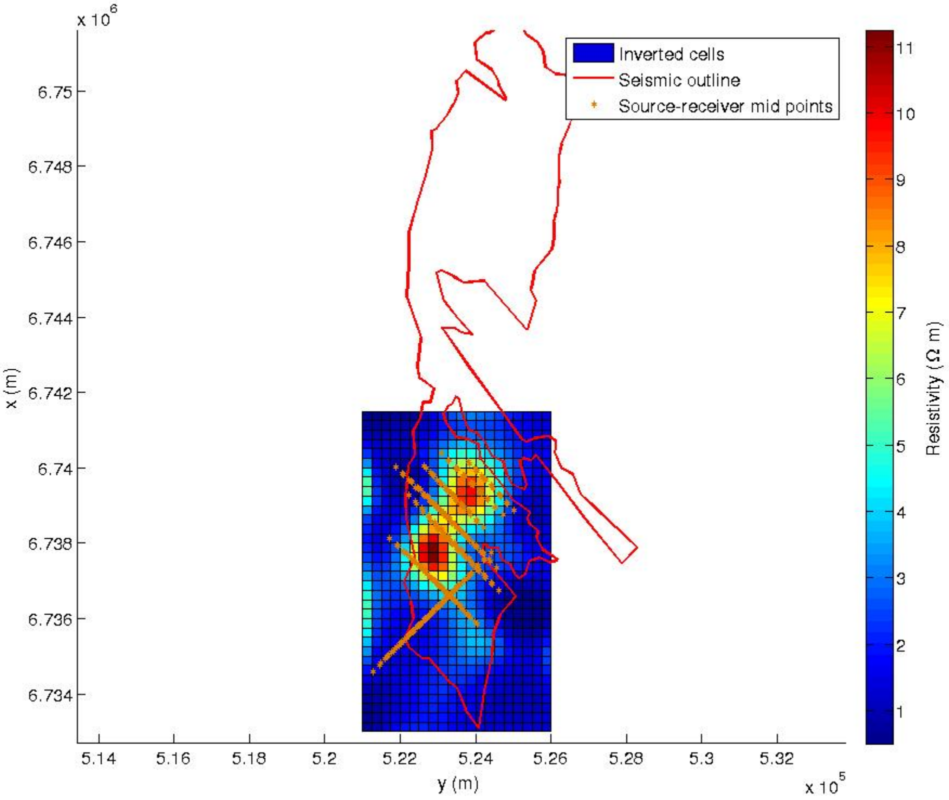

Figure 3: Inversion result. Target depth, from sea surface, is 1450 m and roughly 30 m thick.

burial depth from a priori information. Moreover, it also agrees well with previous results from node system data, as an example, the result in Zach et al. (2009). The integral equation method used, in this case, has shown to be reliable and in some sense sufficient. Finally, the result required less than 20 minutes on a 16 processor computer.

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