Three-dimensional electromagnetic holographic imaging in offshore petroleum exploration

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SUMMARY

Off-shore petroleum exploration nowadays routinely uses the marine controlled-source (MCSEM) survey, which consists of a set of sea-bottom receivers and a moving electrical bipole transmitter. We show that the MCSEM survey with its dense system of transmitters and receivers, is extremely well suited for application of the holography/migration method. The combined EM signal in the receivers forms a broadband EM "hologram" of the sea-bottom geological target. As in optical and radiowave holography, we can reconstruct the volume image of the geological target by "illuminating" this EM hologram with the reference signal. The principles of holography/migration imaging formulated in this paper are applied to the interpretation of an MCSEM survey conducted in the Troll West Gas Province (TWGP), offshore Norway.

INTRODUCTION

A typical sea-bed logging (SBL) survey employs a set of sea-bottom receivers and a moving electrical bipole transmitter. The receivers record the magnitude and the phase of the frequency domain (FD) electromagnetic field generated by the moving transmitter and scattered back by the sea-bottom geoelectrical structures. The combined electromagnetic signal in the receivers can be treated as a broadband EM hologram of the sea-bottom geological target (e.g., a petroleum reservoir). In order to reconstruct the geoelectrical image of the target, we replace a set of receivers with a set of auxiliary transmitters located in the receivers' positions. The strength and the phase of the signal transmitted by these auxiliary transmitters are determined according to the parameters of the observed field in the receivers. These transmitters generate an EM field, which is called the backscattering or the migration field. The vector cross-power spectrum of the background field (the field generated by the original transmitter in a medium without a target) and the backscattering field produces a numerical reconstruction of a volume image of the conductivity distribution (Zhdanov, 2001, 2002).

The marine EM signal frequency is very low, about 1 Hz. In this low frequency range, the EM field propagates in sea-bottom formations according to the diffusion equation (Zhdanov and Keller, 1994), which results in a relatively low resolution of the geoelectrical image obtained by the EM migration. We thus apply the migration iteratively, which improves the resolution of the underground image and allows us to use the principles of regularization and focusing to improve the focus of the target structures. In this paper, we apply the iterative regularization migration algorithm to the interpretation of 1) a complex syntethic model and 2) practical MCSEM data from the Troll West Gas Province.

FREQUENCY-DOMAIN ELECTROMAGNETIC (FDEM) MIGRATION OF MCSEM DATA

Principles of frequency-domain electromagnetic (FDEM) migration of MCSEM data have been described in the previous publications by Zhdanov and Gribenko (2006) and Zhdanov and Ueda (2007).

Let us assume that the sea-bottom receivers are located at the points with radius-vector $\mathbf{r}_j$, $(j = 1, 2, 3, ..., J)$ in some Cartesian coordinate system. Every receiver R_j records electric and magnetic field components of the field generated by an electric bipole transmitter moving above the receivers. We denote this field as $\mathbf{E}_i\ \mathbf{r}_j$, $\mathbf{H}_i\ \mathbf{r}_j$ where i is the index of the corresponding transmitter, T_i , located at the point $\mathbf{r}_i$, $(i = 1, 2, 3, ..., I)$.

According to the definition, the backscattering (migrated) residual field is a field generated in the background medium by a combination of all electric dipole transmitters located at points $\mathbf{r}_i$ with the current moments determined by the complex conjugate residual field $\mathbf{R}^*_{Ej}(\mathbf{r}_i)$ defined as a difference between the background and observed field:

$$\mathbf{R}_{Ej}(\mathbf{r}_i) = \mathbf{E}^b_j(\mathbf{r}_i) - \mathbf{E}^E_j(\mathbf{r}_i) = -\mathbf{E}^{Ea}_j(\mathbf{r}_i). \qquad (1)$$

In the general case of multiple receivers, the migration field is generated in the background medium by all electric dipole transmitters located above all receivers, R_j, whose current moments are determined by the complex conjugate residual field $\mathbf{R}^*_{Ej}(\mathbf{r}_i)$.

Therefore, the total migration field for all receivers can be obtained by summation of the corresponding migration field computed for every individual receiver.

It can be shown that the spatial distribution of the migration field is closely related to the conductivity distribution in the medium. However, one needs to apply the corresponding imaging condition (Zhdanov, 2002) to enhance the conductivity image produced by the EM migration:

$$\sigma_1 \approx -k\left(\mathbf{W}^\star_m \mathbf{W}_m\right)^{-1} \mathbf{l}_0, \qquad (2)$$

where k is a scaling coefficient, $\mathbf{W}_m$ is a model parameter weighting matrix, and $\mathbf{l}^{EH}_0$ is a migration image formed by a cross-power spectrum of the background and migration fields:

$$\mathbf{l}^{EH}_0 = Re \sum_{\omega_n} \left[\ \widetilde{\mathbf{E}}^{bE} \cdot \widetilde{\mathbf{E}}^{mE} \ + \ \widetilde{\mathbf{E}}^{bH} \cdot \widetilde{\mathbf{E}}^{mH}\ \right]. \qquad (3)$$

By weighting the migration image $\mathbf{l}^{EH}_0$ with the matrix $\mathbf{W}_m$, we assure that the observed data are equally sensitive to the conductivity variations within every part of the domain of investigation. As a result, we generate an electrical conductivity

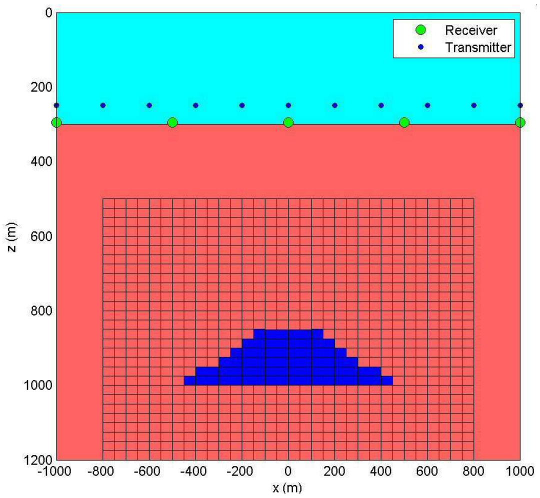

Figure 1: A vertical section of the true resistivity of Model 1 along the survey line.

image which correctly reflects the volume distribution of the anomalous conductivity.

REGULARIZED ITERATIVE MIGRATION

The above described migration imaging can be treated as the first iteration in the solution of an electromagnetic inverse problem. Obviously, we can obtain better imaging results if we repeat the iterations. We can now apply a general scheme of the re-weighted, regularized, conjugate-gradient method in the space of the weighted parameters (Zhdanov, 2002) to form an iterative process for electromagnetic migration.

Thus, we can describe the developed method of iterative migration as follows. On every iteration we calculate the theoretical electromagnetic response $\widetilde{\mathbf{E}}^n$ for the given geoelectrical model σ_{n-1} obtained on the previous step, calculate the residual field between this response and the observed field $\widetilde{\mathbf{R}}_E^n$, and then migrate the residual field. The gradient direction is computed as a sum over the frequencies of the dot product of the migrated residual field and the theoretical response $\widetilde{\mathbf{E}}^n$. Using this gradient direction and the corresponding value of the optimal length of the step k_n, we calculate the new geoelectrical model σ_n.

Note that every iteration of the migration algorithm requires two forward- modeling computations: one to compute the migration field and another one for computing the predicted data at the receivers. In this work, we use a recently developed parallel migration code that is parallelized over the vertical dimension of the migration domain. We also use a modified parallel PIE3D program for calculation of the migration and predicted fields. This enables us to considerably reduce computation time and also model larger problems by increasing the migration domain size or the number of cells used for the migration domain discretization.

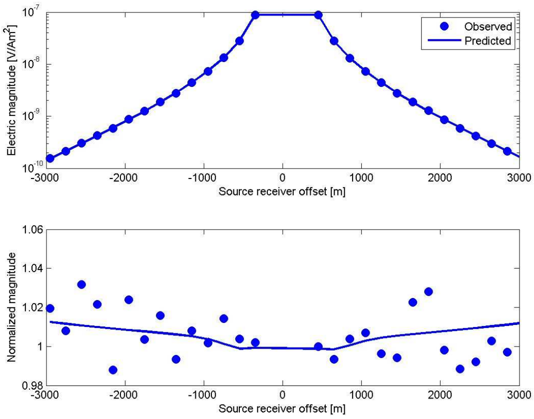

Figure 2: The top panel shows magnitude-versus-offset (MVO) plots of the total electric field, while the bottom panel presents MVO plot of the same field normalized by the absolute values of the background electric fields. The observed data contaminated by noise are shown by the dots. The solid line corresponds to the data predicted for the migration resistivity model.

MIGRATION OF SYNTHETIC MCSEM DATA

We assume that a synthetic MCSEM survey is conducted in relatively shallow water with a sea depth of 300 m. The survey consists of eleven sea-bottom receivers and an electric dipole transmitter moving along a line passing directly above the receivers at an elevation 50 m above the seafloor. The transmitter generates a frequency-domain EM field every 200 m along the towing line, which is extended from -3000 m to 3000 m. Eleven seafloor electric receivers are located 5 m above the sea bottom along the x coordinates from $x = -2500$ to $x = 2500$ m with 500 m spacing. The separation between receivers is 500 m. The background layered geoelectrical model consists of a seawater layer with a thickness of 300 m, a resistivity of 0.25 Ohm-m, and homogeneous sea-bottom sediments with a resistivity of 1 Ohm-m. There is an anticlinal oil reservoir located in the seafloor sediments at a depth between 850 m and 1000 m below sea level with a resistivity of 100 Ohm-m and a maximum horizontal diameter of 900 m. A vertical section of the true resistivity model along the survey line is shown in Figure 1. The migration domain is discretized with a cell size of 25×25×25 m, resulting in 28,672 cells.

The transmitter generates an EM field at the frequencies of 0.25 and 0.75 Hz. The receivers measure the in-line component of the electric fields, E_x, and the cross-line component of the magnetic fields, H_y, simultaneously. The synthetic MCSEM data for this model were calculated using the parallel integral equation forward modeling code PIE3D developed by Yoshioka and Zhdanov (2007).

The observed data for this model can be represented as the plots of the total electric field E_x and magnetic field H_y recorded in the receivers and the plots of the same fields normalized by the absolute values of the background electric and magnetic fields respectively (Figures 2 through 3). Note that we have

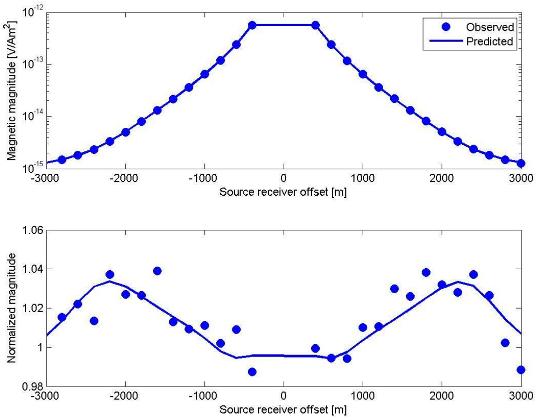

Figure 3: The top panel shows magnitude-versus-offset (MVO) plots of the total magnetic field, while the bottom panel presents MVO plot of the same field normalized by the absolute values of the background magnetic fields. The observed data contaminated by noise are shown by the dots. The solid line corresponds to the data predicted for the migration resistivity model.

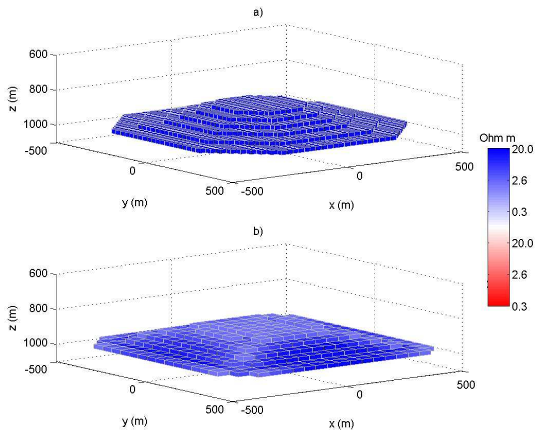

Figure 4: The figure shows (a) the true model and (b) the final 3D holographic image obtained by joint iterative migration of the EM data for Model 1 with an a priori model.

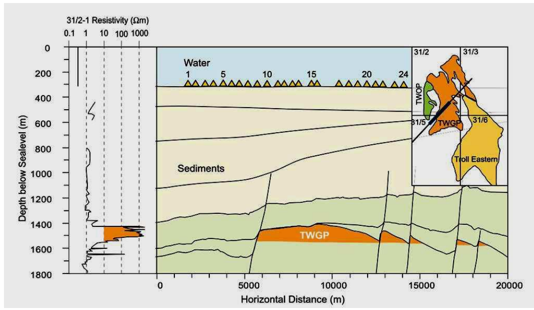

Figure 5: A simplified geological model along the MCSEM survey line in the Troll West Gas Province (TWGP), offshore Norway (Johansen and Bhuyian, 2005).

contaminated the synthetic observed data with random Gaussian noise. The noise level increases linearly from 1% at zero offset up to 7% at 10000 m offset to simulate the typical noise behavior in field MCSEM data.

We utilize joint 3D migration of the electric and magnetic field data for Model 1. We can realize a full 3D migration for the data observed by a few receivers located along a profile, because we generate a 3D migration field by a set of reciprocal transmitters. The migration field generated by these transmitters propagates within the medium in all directions, creating a 3D image of the target.

We perform an iterative migration calculation. We run 35 iterations with an anticlinal a priori model with resistivity 3 Ohm-m that encloses the true reservoir. The a priori model is turned off for the last five iterations. The final total misfit is around 20%. The reservoir location and the shape are resolved fairly well (Figure 4).

In Figures 2 and 3 one can also see the predicted data computed for the migration model shown in Figure 4.

The migration of the EM data for this model was run on an Opteron workstation with four 2.2 GHz CPUs, requiring about 500 MB of RAM per processor, that is 2 GB of RAM total. The 35 iterations took a little under five hours to finish.

MIGRATION OF TROLL GAS PROVINCE MCSEM DATA

We have applied the 3D EM migration techniques, including both fast migration imaging and iterative migration, to the interpretation of the marine EM data collected by EMGS and Statoil at the Troll West Gas Province (TWGP), offshore Norway (Johansen and Bhuyian, 2005).

A marine CSEM survey was conducted using 24 receivers deployed at the sea bottom along a line crossing the Western Gas Province. The transmitter was a horizontal electric bipole (HEB) with a length of 230 m towed by the survey vessel. The transmitting bipole generated a sine wave signal with a base frequency of 0.25 Hz. Figure 5 shows a simplified geological model along the MCSEM survey line.

We should note that there are several publications dedicated to the inversion of the Troll MCSEM data (Chen and Hou, 2004; Hoversten and Vasco, 2006; Gribenko and Zhdanov, 2007). In the paper by Hoversten and Vasco (2006), the finite difference based inversion was used, while Gribenko and Zhdanov (2007) applied the rigorous inversion based on integral equation (IE) forward modeling. Notably, in all these inversions some a priori model of the gas reservoir was used to produce a better geoelectrical image.

In order to apply the migration algorithm developed in this paper to the Troll MCSEM data, we have selected a 1D layered background structure based on 1D inversion (with a known water depth equal to 338 m).

We have selected a domain of migration 21 km and 9 km in

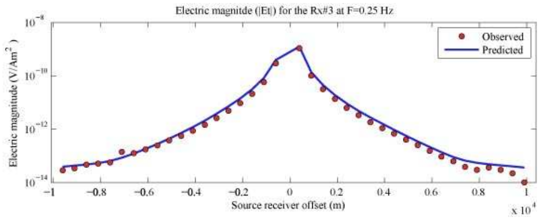

Figure 6: Amplitude-versus-offset (AVO) plots of the Troll Field data at a frequency of 0.25 Hz. The red dots show the observed in-line electric field data, while the predicted data for a model obtained by iterative migration are plotted by the solid blue line.

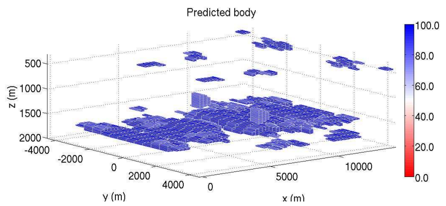

Figure 7: A 3D holographic image of Troll West Gas Province (TWGP), North Sea, obtained by iterative migration.

the x and y -directions, respectively, and 1.5 km deep in the vertical (z) direction from 400 m to 1900 m below sea level, where the x axis of the Cartesian coordinates is oriented along the MCSEM profile, and the z axis is directed downward. This migration domain is discretized in $84 \times 18 \times 60 = 90,720$ cells, with the cell sizes having 250, 500, and 25 m in the x, y and z directions, respectively. Having previous knowledge of the seismic profile, we designed an a priori model with the top layer in the x direction being the seismic lines that mark the top of the reservoir in Figure 5 and with the bottom layer at 1575 m with a resitivity of 3 Ohm-m. We ran 100 iterations of the migration algorithm. The a priori model was turned on only during the initial ten iterations. The remaining 90 iterations were computed without an a priori model.

The amplitude-versus-offset (AVO) plots of the Troll Field data at a frequency 0.25 Hz are shown in Figure 6. The red dots show the observed in-line electric field data, while the predicted data for a model obtained by iterative migration are plotted by a solid blue line.

Figure 7 represents a 3D holographic image of the geoelectrical model obtained by migration imaging.

Figure 8 represents overlapping of migration results with the geological interpreted section. One can see good agreement between the migration results and the geological section.

The holographic/migration imaging method, which has been developed in this paper, has the ability to detect a strong resistivity anomaly in the area of the Jurassic sandstone reservoir.

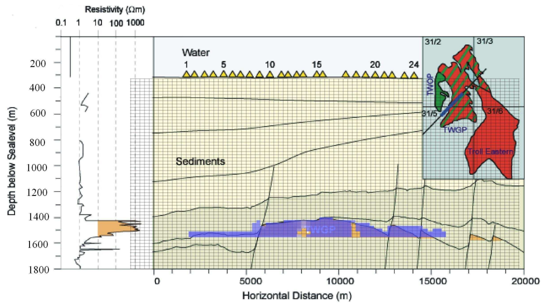

Figure 8: Cross section of the result of iterative migration overlapping on the geological cross section. Grid lines denote the migration domain.

CONCLUSION

Electromagnetic migration was originally introduced for interpretation of land EM data. However, this technique is most effective in the case of relatively dense EM surveys, which are difficult to implement on land. The MCSEM survey with its dense system of transmitters and receivers, happens to be extremely well suited to application of the migration technique. In this paper we illustrate all the basic principles of EM migration in application to MCSEM data interpretation.

In order to improve the resolution and quality of the migration image, we apply an iterative migration by repetitive backscattering of the residual field within the background medium. The backscattered field is computed using a fast parallel IE method. By including the focusing stabilizer in the iterative migration scheme, we produce a sharp and focused image of the target with focusing iterative migration.

The holographic/migration imaging method has been applied to interpretation of the practical MCSEM data acquired at Troll West Gas Province by Statoil and EMGS. The interpretation results also show that migration can be treated as a prospective method of MCSEM data interpretation.

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EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2008 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

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