Iterative migration in marine CSEM data interpretation

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SUMMARY

In this paper we consider an application of the ideas of electromagnetic (EM) migration to the interpretation of a typical marine controlled-source (MCSEM) survey, which consists of a set of sea-bottom receivers and a moving electrical bipole transmitter. The 3-D interpretation of the MCSEM data is a very challenging problem because of the enormous amount of computations required in the case of the multi-transmitter and multi-receiver data acquisition systems used in these surveys. At the same time, we show that the MCSEM surveys with their dense system of transmitters and receivers happen to be extremely well suited for application of the migration method. In order to speed up the computation of the migration field, we apply a fast form of integral equation (IE) solution based on the multigrid quasi-linear (MGQL) approximation. The principles of the migration imaging formulated in this paper are tested on a typical model of a sea-bottom petroleum reservoir.

INTRODUCTION

During the last few years marine controlled-source electromagnetic (MCSEM) surveys have become widely used for offshore petroleum exploration. The main target of this survey is the sea-bottom petroleum reservoir, which is usually characterized by a low electrical conductivity anomaly within the relatively conductive sea-bottom sediments. There is growing interest in the interpretation of the MCSEM data based on 3-D geoelectrical models. The conventional approach based on standard 3-D forward modeling and inversion meets significant difficulties because of the enormous amount of computations required in the case of the multi-transmitter and multi-receiver data acquisition systems typical for marine CSEM surveys. There is an alternative approach to the solution of this problem, which is based on the ideas of electromagnetic holography and/or migration (Zhdanov, 1981, 1988; Zhdanov and Frenkel, 1983a,b; Zhdanov and Keller, 1994; Zhdanov et al., 1996; Zhdanov, 1999, 2001, 2002; Tompkins, 2004; Mitte et al., 2005; Wan and Zhdanov, 2005a,b). In the current paper we consider an application of this approach to the interpretation of a typical sea-bed logging (SBL) survey which consists of 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 forms a broad-band EM hologram of the sea-bottom geological target (e.g. 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 is 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 backscattering field produces a numerical reconstruction of a volume image of conductivity distribution Zhdanov (2001).

We should note, however, that the frequency of the EM signal, used in the marine EM, 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 numerical algorithm described above. In order to improve the resolution of the EM holographic imaging, we should apply the migration iteratively. The development of the corresponding method of iterative migration with the application to the SBL data constitutes the main subject of the present paper.

FREQUENCY DOMAIN ELECTROMAGNETIC (FDEM) MIGRATION OF THE SBL DATA

Let us consider a typical SBL survey consisting of a set of electric field receivers located at the sea bottom, and an electric bipole transmitter moving at some elevation above the sea bottom, as shown in Figure 1. We assume that the electrical conductivity in the model can be represented as a sum of a background conductivity $\sigma = \sigma_b$ and an anomalous conductivity $\Delta\sigma$ distributed within some local inhomogeneity D associated with the location of the petroleum reservoir.

The 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 $\mathbf{E}_i\left(\mathbf{r}_j\right), \mathbf{H}_i\left(\mathbf{r}_j\right)$ where i is the index of the corresponding transmitter, T_i, located at the point $\mathbf{r}_i, (i = 1,2,3,\ldots,I)$.

We introduced the residual electric field, $\mathbf{R}_{Ej}\left(\mathbf{r}_i\right)$ as a difference between the background and observed field:

$$\mathbf{R}_{Ej}\left(\mathbf{r}_i\right) = \mathbf{E}_j^b\left(\mathbf{r}_i\right) - \mathbf{E}_j^E\left(\mathbf{r}_i\right). \tag{1}$$

According to the definition (Zhdanov, 2002), 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 $\mathbf{R}_{Ej}^*\left(\mathbf{r}_i\right)$ according to the following formula:

$$\mathbf{E}_j^m\left(\mathbf{r}\right) = \mathbf{E}_j^m\left(\mathbf{r};\mathbf{R}_{Ej}^*\right) = \sum_{i=1}^{I} \mathbf{G}_E\left(\mathbf{r} \mid \mathbf{r}_i\right) \mathbf{R}_{Ej}^*\left(\mathbf{r}_i\right), \tag{2}$$

where the lower subscript j shows that we migrate the field observed by the receiver R_j, and $\mathbf{G}_E$ is the electric Green's tensor for the layered (background) conductivity model σ_b.

In a 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, having the current moments determined by the complex conjugate residual field $\mathbf{R}_{Ej}^*\left(\mathbf{r}_i\right)$:

$$\mathbf{E}^m\left(\mathbf{r}\right) = \sum_{j=1}^{J}\sum_{i=1}^{I} \mathbf{G}_E\left(\mathbf{r} \mid \mathbf{r}_i\right) \mathbf{R}_{Ej}^*\left(\mathbf{r}_i\right). \tag{3}$$

According to formula (2), we have:

$$\mathbf{E}^m\left(\mathbf{r}\right) = \sum_{j=1}^{I} \mathbf{E}_j^m\left(\mathbf{r}\right). \tag{4}$$

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

MIGRATION IMAGING CONDITION

Formula (2) and (3) allows us to reconstruct the migration field everywhere in the medium under investigation. It can be shown that this transformation is stable with respect to the noise in the observed data. At the same time the spatial distribution of the migration field is closely related to the conductivity distribution in the medium. How-

ever, one needs to apply the corresponding imaging conditions to enhance the conductivity image produced by the EM migration. This imaging condition was introduced in Zhdanov (2002) as follows:

$$\sigma_1 \approx \alpha^{-1} \left(W_m^{\star} W_m\right)^{-1} \mathrm{Re} \sum\nolimits_{\omega_n} \left(\widetilde{\mathbf{E}}^{b*} \cdot \widetilde{\mathbf{E}}^{m*}_{W_d}\right). \quad (5)$$

We have demonstrated above that the migration field represents a backscattering field produced by illuminating the background medium by artificial transmitters located in the positions of the receivers and operated by electric dipoles with the current moments determined by the complex conjugate residual field $\mathbf{R}^*_{Ej}(\mathbf{r}_i)$ according to formulas (2) and (3). Therefore, the imaging condition (5) is nothing else but cross power spectra of the background and the migration (backscattering) electric fields (Zhdanov, 2001). We will call the conductivity distribution obtained by formula (5) a *migration apparent conductivity.*

REGULARIZED ITERATIVE MIGRATION

It was demonstrated in Zhdanov (2002), that we can obtain better imaging results if we repeat the migration iteratively.

$$\sigma_n = W_m^{-1} \sigma_n^w. \quad (6)$$

We can describe the developed method of iterative migration as follows. On every iteration we calculate the theoretical electromagnetic response $\mathbf{E}^n$ for the given geoelectrical model σ_n, obtained on the previous step, calculate the residual field between this response and the observed field, $\mathbf{R}^n_E$, 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 $\mathbf{E}^n$, according to formula

$$\mathbf{l}_n = \mathrm{Re} \sum\nolimits_{\omega_n} \left(\mathbf{E}_n \cdot \mathbf{E}^m_n\right), \quad (7)$$

where the field $\mathbf{E}^m_n$ is obtained by the migration of the residual field found on the iteration number n. Using this gradient direction length of the step k_n (Zhdanov, 2002), we calculate the new geoelectrical model σ_n on the basis of expressions (5). The iterations are terminated when the misfit reaches the level of the noise.

The migration apparent conductivity (5), introduced above, is used as the first iteration in this iterative process.

It was demonstrated in Portniaguine and Zhdanov (1999) and Zhdanov (2002) that images with sharp boundaries can be recovered by regularized inversion algorithms based on a special family of stabilizing functionals. Particularly, the minimum support (MS) functional was found to be useful in the solution of this problem. It selects the inverse model within the class of models with a minimum volume of a domain with anomalous parameter distribution. This class of models describes the compact objects which are typical targets, for example, in mineral and hydrocarbon exploration. A similar approach can be applied in the case of migration transformation by substituting the focusing stabilizers for the minimum norm functional in equation (**??**). We call this technique focusing iterative migration. Numerical implementation of the focusing migration is similar to focusing inversion (Zhdanov, 2002).

MIGRATION OF SYNTHETIC MCSEM DATA

We have analyzed the principles of the iterative EM migration outlined above using as an example the synthetic MCSEM data, computed for a model shown in Figure 1. The model is formed by a horizontally layered background consisting of a conductive seawater layer with a resistivity of 0.25 Ohm-m and a thickness of 500 m, and sea-bottom sediments with a resistivity of 1 Ohm-m. A rectangular resistive petroleum reservoir with a thickness of 100 m and a resistivity of 100 Ohm-m is located at a depth of 300 m below the sea bottom. The mobile horizontal (x- oriented) electric dipole (HED) transmitter generates an EM

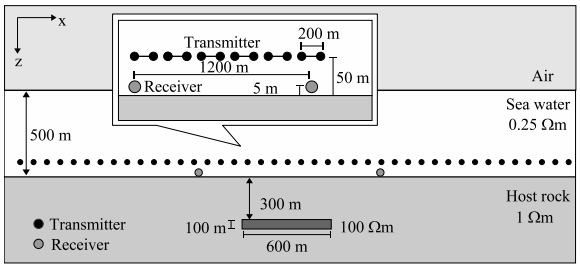

Figure 1: Sketch of the SBL survey and model design.

field every 100 m along a line parallel to the horizontal axis x and elevated at 50 m above the sea bottom. Two seafloor electric receivers are located 5 m above the sea bottom at the points with x-coordinates equal to -600 m and 600 m, respectively. The transmitter generates an EM field at the very low frequencies of 0.1, 0.5, and 1 Hz. The receivers measure the in-line component of the electric field, E_x, only. The synthetic MCSEM data for this model were calculated using the INTEM3DQL forward modeling code (Ueda and Zhdanov, 2006).

The observed data for this model can be represented as the plots of the total electric field E_x recorded in the receivers normalized by the absolute value of the background electric field (Figures 2). We show also an amplitude versus offset (AVO) plot of the normalized field in the same figures. One can see in these plots that the anomalous parts of the AVO curves are located outside the reservoir at the far offsets. This fact illustrates the importance of recording the electric field for large transmitter-receiver separations. We have applied the focusing migration to produce a sharp image of the reservoir. Figure 3 presents the cross power spectra between the total electric field at the current iteration # n ($n = 1, 3, 5, 7, 9, 10, 11, 13, 15, 17, 19, 20$) and the focusing migration of the corresponding residual field. We can see that already at iteration #13 the cross power spectrum produces a clear and sharp image of the reservoir. The inverse resistivity images for different iterations of focusing migration are shown in Figure 4.Figure 5 shows the final inverse resistivity image obtained by focusing migration.

The plots in Figure 6 correspond to the observed and predicted data computed for the inverse model obtained by the focusing migration. A volume image of the focusing migration result is shown in Figure 7. It is interesting to see from these figures that migration of the MCSEM data collected along just one observational profile can produce a reasonable volume image of the true 3-D reservoir.

In order to study the effect of noise on the migration results, we have contaminated the observed data with 3% random noise. The noisy data are shown in Figure 8. The focusing migration image is presented in Figure 9. One can see that the location and shape of the reservoir is still resolved well on this image obtained from noisy data.

CONCLUSION

Electromagnetic migration has been originally introduced for interpretation of land EM data. However, this technique is most effective in

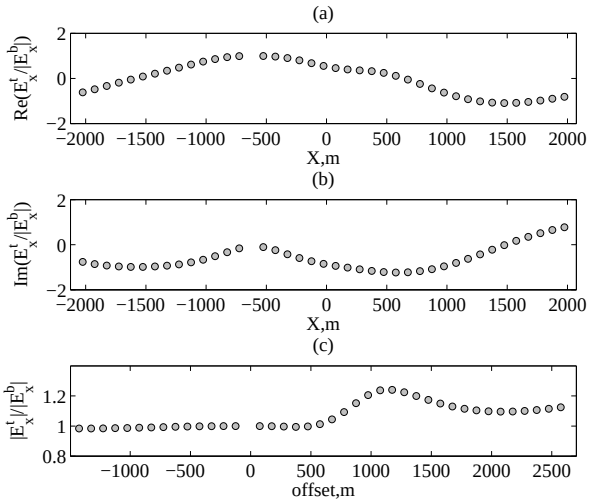

Figure 2: (a) Real and (b) imaginary parts of the x-component of the total electric field normalized by the amplitude of the background Ex field for the transmitter x=-600. Panel (c) shows an amplitude versus offset (AVO) plot of the normalized field.

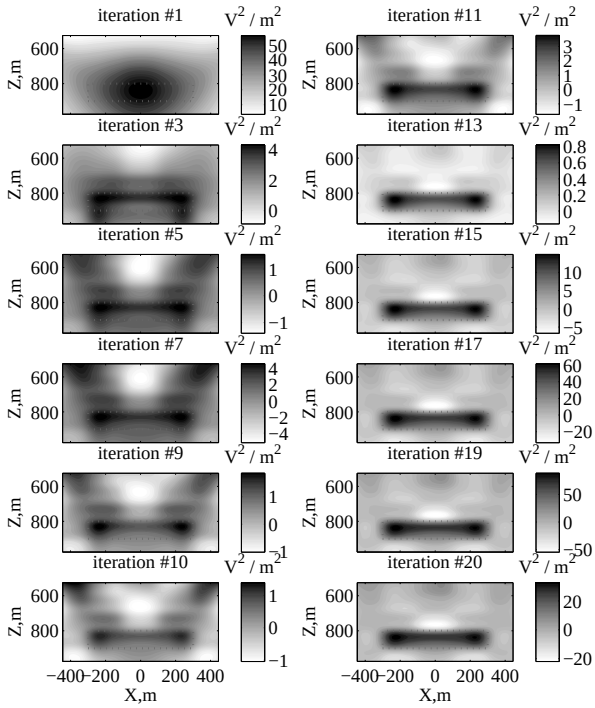

Figure 3: Focusing migration: cross power spectra between the total electric field E_n at the current iteration #n and the migration of the corresponding residual field.

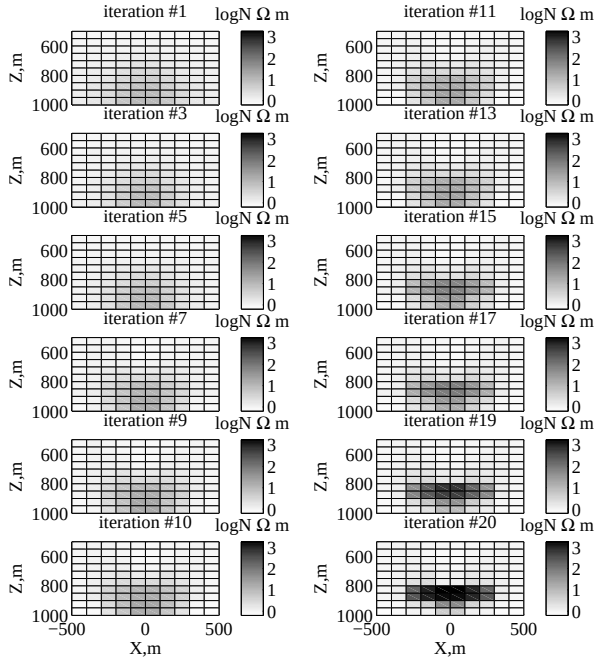

Figure 4: Inverse resistivity cross section images for different iterations of the focusing migration.

the case of relatively dense EM surveys, which are difficult to implement on land. The MCSEM surveys with their dense system of transmitters and receivers happen to be extremely well suited for application of the migration technique. In this paper we illustrate all the basic principles of EM migration in application to the MCSEM data interpretation. We show that, by using the reciprocity principle the system of moving transmitters and fixed sea-bottom receivers can be represented by a survey with fixed sea-bottom transmitters and multiple sea-water receivers. The migration (backscattering) field is produced by a combination of all electric dipole transmitters operating simultaneously according to the recorded signal in the receivers. The cross power spectra of the migration and background electric fields generate a volume image of the anomalous conductivity distribution in sea-bottom formations.

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 form of IE solution based on the multigrid quasi-linear (MGQL) aproximation. By including the focusing stabilizer in the iterative migration scheme, we produce a sharp and focused image of the target with the focusing iterative migration.

The basic principles of the migration imaging formulated in this paper are implemented in the draft version of the computer code and are tested on a typical model of a sea-bottom petroleum reservoir. The numerical results show that migration can be treated as a prospective method of MCSEM data interpretation. Future research will be focused on investigation of full 3-D MCSEM surveys and interpretation of the MCSEM data over more complex geological targets.

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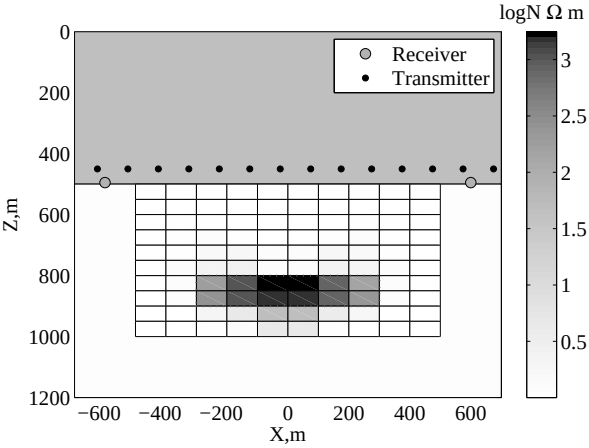

Figure 5: Cross-section of the final inverse resistivity image obtained by focusing migration at Y=-50 m.

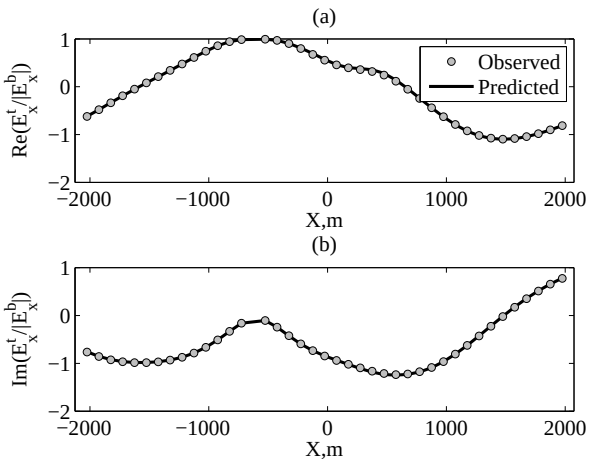

Figure 6: Normalized observed data and predicted data in a receiver located at $x = -600$ m computed for a model obtained by iterative migration The top panel shows the real part of the total electric field normalized by the amplitude of the background electric field while the bottom panel displays the imaginary part of the total electric field normalized by the amplitude of the background electric field.

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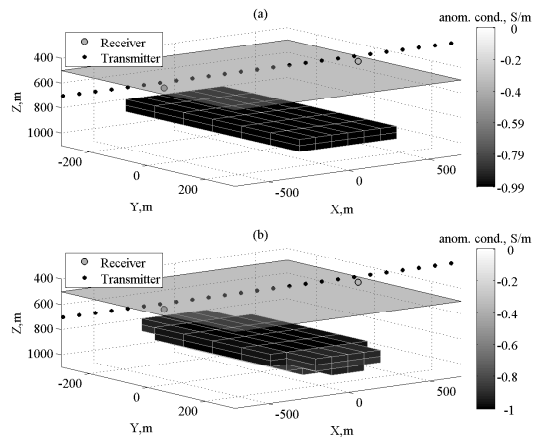

Figure 7: 3-D volume rendering images of (a) the true model and (b) the focusing iterative migration result.

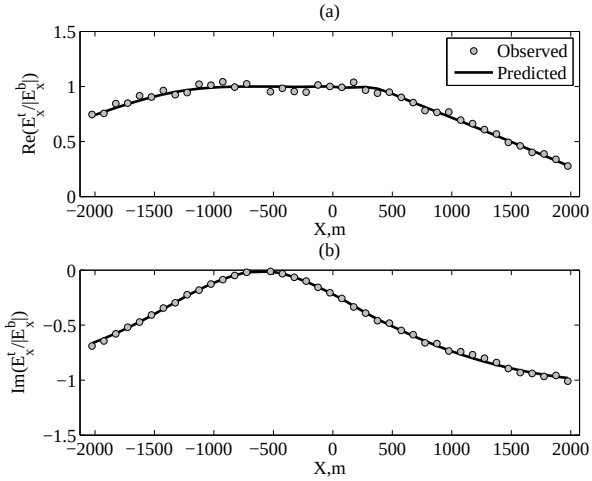

Figure 8: Normalized observed noisy data and predicted data in a receiver located at $x = -600$ m computed for a model obtained by iterative migration The top panel shows the real part of the total electric field normalized by the amplitude of the background electric field while the bottom panel displays the imaginary part of the total electric field normalized by the amplitude of the background electric field.

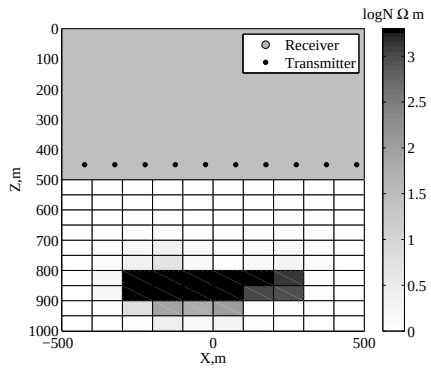

Figure 9: Cross-section of the final inverse resistivity image obtained by focusing migration of noisy data at Y=-50 m.

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