Multiple inversion scenarios for enhanced interpretation of marine CSEM data using iterative migration: A case study for the Shtokman gas field, Barents Sea

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Summary

The integration of shared earth modeling and robust 3D CSEM modeling and inversion is the key to deriving a reliable quantitative interpretation from marine controlled-source electromagnetic (CSEM) data. Workflows should make use of all available subsurface data and enable the interpreter to select the most geologically relevant resistivity model from the multitude of models that satisfy the same CSEM data. To this end, we present our implementation of an iterative migration method for CSEM data, equivalent to rigorous inversion. Our iterative migration method is based on the 3D integral equation method with inhomogeneous background conductivity and focusing regularization with a priori terms. Here, we will show that focusing stabilizers recover more geologically realistic models with sharper geoelectric contrasts and boundaries than traditional smooth stabilizers. Additionally, we will show that focusing stabilizers have better convergence properties than smooth stabilizers. Our method is implemented in a fully parallelized code, which makes it practical to run large-scale 3D iterative migration on multi-component, multi-frequency and multi-line CSEM surveys for models with millions of cells. We present a suite of interpretations obtained from different migration scenarios for a 3D CSEM feasibility study computed from a detailed model of the Shtokman gas field in the Russian sector of the Barents Sea.

Introduction

The premise for the various marine CSEM methods is sensitivity to the lateral extents and thicknesses of resistive bodies embedded in conductive hosts. For this reason, CSEM methods have been applied to de-risking exploration and appraisal with direct hydrocarbon indication (Hesthammer et al. 2010). Methods for interpreting CSEM data are complicated by the very small responses of hydrocarbon-bearing reservoir units when compared to the total fields. Quantitative interpretation of CSEM data is inherently reliant on iterative inversion methods since the data cannot simply be separated or transformed with linear operators as per seismic methods. Best practice is to run multiple 3D inversion scenarios in order to enable interpreters to vary their inversion parameters so as to explore alternative resistivity models that satisfy the data, and select the most geologically plausible ones for subsequent interpretation. This practice identifies any artifacts that may arise from interpreting a single resistivity model. Alternative models may also be used to reveal what additional data, if any, are needed to further constrain the interpretation. Generation of these alternative models requires rigorous but fast 3D inversion methods. Rigorous inversion methods are not the most practical, as the sensitivity matrix needs to be constructed and stored at each iteration for the many transmitter-receiver combinations in a CSEM survey. Our more pragmatic approach is based on iterative electromagnetic migration implemented in a reweighted regularized conjugate gradient method as to rigorously compute the gradient directions without needing to explicitly construct the sensitivity matrix or its products. In terms of 3D CSEM inversion, geological prejudice is introduced via regularization; whether that is an a priori model, data or model weights, model bounds and/or by the choice of stabilizing functional. Resistivity models are often obtained from regularization with smooth stabilizing functional; the first or second derivatives of the resistivity distribution are minimized, resulting in smooth distributions of the resistivity. This type of smooth solution allegedly satisfies Occam's razor since it is claimed to produce the most "simplistic" model for the data. Unfortunately, there is a tendency to deliver the single resistivity model as "the" solution. In reality, this type of model is the least relevant to economic geology. As we will show, the use of focusing rather than smooth stabilizers allows us to recover stable and geologically realistic models with sharper geoelectric boundaries and contrasts (Figure 1).

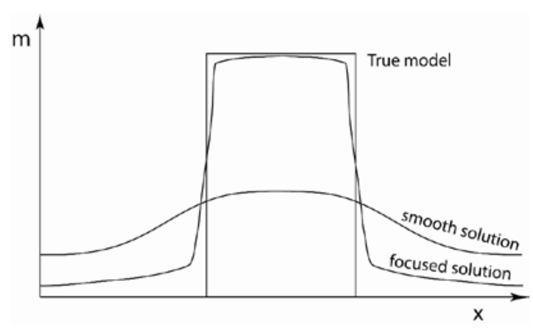

Figure 1. *A smooth stabilizer will recover a model with a smooth distribution of model parameters. A focusing stabilizer will recover a model with sharper boundaries and contrasts, and will be closer to the true model.*

Iterative electromagnetic migration

The physical principles of electromagnetic migration parallel those underlying optical holography and seismic migration; i.e., the recorded fields scattered by an object form a hologram from which one can subsequently reconstruct an image of the object by "illuminating" the hologram (Zhdanov, 1988). It has been demonstrated that migration provides an alternative method for evaluating adjoint operators and when applied iteratively, migration is analogous to inversion in providing a rigorous solution to the corresponding inverse problem (Zhdanov, 2001, 2002, 2009). At each iteration, we calculate the predicted fields that would be measured at the receiver positions due to a 3D resistivity model. We minimize the computational burden by exploiting the reciprocity theorem. We then calculate the residual fields as the difference between the observed and predicted data. These residual fields are then migrated. The gradient direction is computed as the integral of the dot product of the predicted and migration fields. This gradient direction and its associated step length are used to obtain an updated resistivity model. The optimal value of the regularization parameter is selected according to the principles of regularization theory. The process is then repeated until the misfit reaches a preset threshold, or the maximum number of iterations is reached. The reweighted regularized conjugate gradient method is used as the basis for iterative migration. We provide the option to regularize the migration with a choice of stabilizing functional, as will be discussed in the next section. The modeling is based on the 3D integral equation method with inhomogeneous background conductivity. This enables models with arbitrary geoelectric complexity to be migrated. We have implemented our iterative migration method in a fully parallelized code, making it practical to run multiple inversion scenarios as described above.

Choosing a stabilizing functional

Regardless of the iterative scheme used, all regularized inversions seek to minimize the Tikhonov parametric functional, $P^{\alpha}(m)$:

$$P^{\alpha}(m) = \phi(m) + \alpha s(m) \rightarrow min,$$

where $\phi(m)$ is a misfit functional of the observed and predicted data, $s(m)$ is a stabilizing functional and α is the regularization parameter that balances (or biases) the misfit and stabilizing functional (Zhdanov 2002). The stabilizing functional incorporates information about the class of models used in the inversion. The choice of stabilizing functional should be based on the user's geological knowledge and prejudice. In this section, we will briefly describe the different smooth and focusing stabilizers. A minimum norm (MN) stabilizer will seek to minimize the norm of the difference between the current model and an a priori model:

$$s_{MN}(m) = \int_V \left(m - m_{apr}\right)^2 dv,$$

and usually produces a relatively smooth model. The Occam (OC) stabilizer implicitly introduces smoothness with the first derivatives of the model parameters:

$$s_{OC}(m) = \int_V \left(\nabla m - \nabla m_{apr}\right)^2 dv,$$

and produces smooth resistivity models, which bear little resemblance to economic geology. Its use can also result in spurious oscillations and artifacts when the resistivity is discontinuous. Alternatively, the use of focusing stabilizers makes it possible to recover models with sharper geoelectric boundaries and contrasts. We refer the reader to Zhdanov (2002, 2009) and Portniaguine and Zhdanov (1999, 2005) for further details. First, we present the minimum support (MS) stabilizer:

$$s_{MS}(m) = \int_V \frac{\left(m - m_{apr}\right)^2}{\left(m - m_{apr}\right)^2 + e^2} dv,$$

where e is a focusing parameter introduced to avoid singularity when $m = m_{apr}$. The minimum support stabilizer minimizes the volume with non-zero departures from the a priori model. Thus, a smooth distribution of all model parameters with a small deviation from the a priori model is penalized. Focused distribution of the model parameters is less penalized. Similarly, we present the minimum vertical support (MVS) stabilizer:

$$s_{MVS}(m) = \int_V \frac{\left(m - m_{apr}\right)^2}{\int_S \left(m - m_{apr}\right)^2 ds + e^2} dv,$$

where S is a horizontal section from the inversion domain. This minimizes the thickness of the volume with non-zero departures from the a priori model. Finally, we present the minimum gradient support (MGS) stabilizer:

$$s_{MGS}(m) = \int_V \frac{\nabla(m - m_{apr}) \cdot \nabla(m - m_{apr})}{\nabla(m - m_{apr}) \cdot \nabla(m - m_{apr}) + e^2} dv,$$

which minimizes the volume of model parameters with non-zero gradient.

Case study – Shtokman gas field

The Shtokman gas field lies in the centre of the Russian sector of the Barents Sea, about 500 km north of the Kola Peninsula. It is currently operated by a joint venture between Gazprom, Total and StatoilHydro. The Shtokman gas field is one of the world's largest known natural gas fields, with reserves of 3.8 tcm of gas and 37 mln t of gas condensate. The Shtokman gas deposit is formed by an anticlinal four-way dip structure containing gas condensate in its crest zone. The productive horizons are located within the Middle Jurassic sandstones. A 3D geoelectric model of the Shtokman field was constructed based on available geological and geophysical information. This model was used for simulating 3D MCSEM surveys at 0.25 Hz, 0.5 Hz and 0.75 Hz.

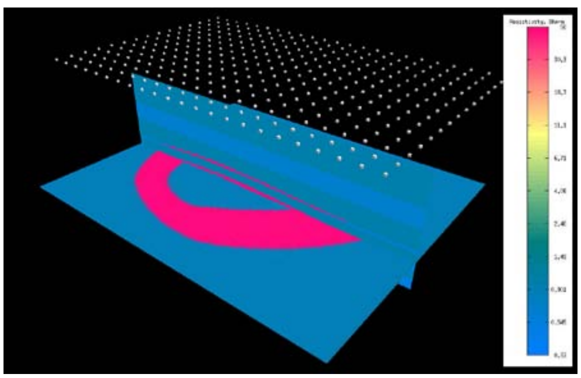

Figure 2. *3D view of the Shtokman resistivity model, with three of the four reservoir units shown. The vertical section corresponds to those vertical cross-sections shown in subsequent figures. The horizontal section shows the extent of the main reservoir unit. Receiver positions are denoted by the grey cubes. A vertical exaggeration of 6 was used in this image.*

A number of migration scenarios were considered. In each case, the migration domain was 44 km x 40 km x 3 km in Easting, Northing and depth. We prepared different combinations of the multi-frequency data for migration over the entire survey area: inline electric field only, inline electric and transverse magnetic fields, as well as inline and vertical electric and transverse magnetic fields. No noise was added to any of the data so we could effectively compare the performance of each stabilizer. The datasets corresponding to each data combination were then migrated with different stabilizers: Occam, minimum norm, minimum support, minimum vertical support, and minimum gradient support. All scenarios were run for a maximum of 26 iterations rather than a misfit tolerance for the purpose of benchmarking performance. All scenarios commenced with an inhomogeneous background conductivity distribution corresponding to the known background structure. With no a priori model of the reservoir units, we don't expect to be able to resolve the stacked reservoir units of the Shtokman gas field. What we do expect, however, is to recover a feature with a general shape and conductivity-thickness product, which is comparable to the stacked reservoir units. This is a well known limitation of the CSEM method's resolution.

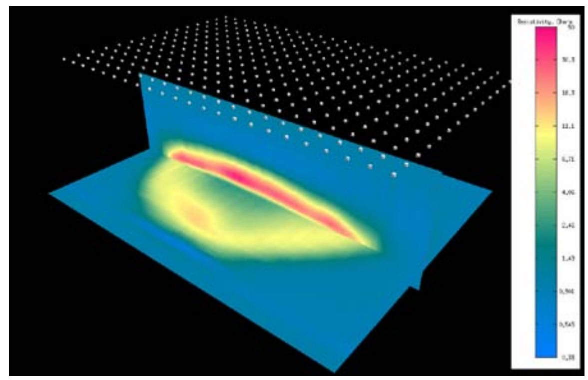

Figure 3. *3D view of the Shtokman resistivity model obtained from the joint iterative migration of the inline and vertical electric and transverse magnetic fields using the MGS stabilizer. The sections correspond to those shown in Figure 2. A vertical exaggeration of 6 was used in this image.*

Figure 5 represents results for the different migration scenarios at their final iterations. Though the actual resistivity models are 3D, we show only vertical cross-sections through each model for the ease of visual inspection of model quality. Panel (a) shows that migration with the Occam stabilizer converged to produce a very smooth resistivity model bearing the least resemblance to the actual resistivity model shown in Figure 2. Migration with the minimum norm stabilizer also produced smooth resistivity models, though not as smooth as the one produced with the Occam stabilizer. Models with sharper geoelectric boundaries and contrasts were obtained using the family of focusing stabilizers. These resistivity models bear the most resemblance to the actual geology as they recovered the anticlinal trends of the Shtokman reservoir units (Figure 3). We compared the convergence of the misfit, which we define as the norm of difference between the normalized observed and predicted data (Figure 4). For each scenario, the family of focusing stabilizers had similar near-quadratic convergence to lower misfits. We noticed that migration with the smooth stabilizers had the slowest convergence. In other words, focusing stabilizers produced better results in less time compared to smooth stabilizers. Though not shown here due to space limitations, our results also show noticeable improvement in the quality of the recovered resistivity models as the transverse magnetic and then vertical electric fields are added to the CSEM data prepared for migration.

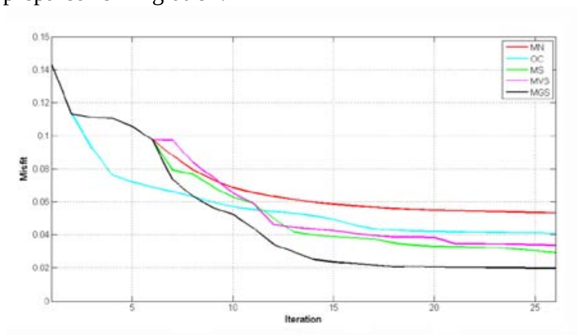

Figure 4. *Convergence of the misfit for the following stabilizers: Occam (OC), minimum norm (MN), minimum support (MS), minimum vertical support (MVS), and minimum gradient support (MGS). These convergence plots are shown for the iterative migration of the inline electric field only.*

Conclusions

3D inversion of CSEM data is inherently non-unique; multiple models will satisfy the same data. Multiple inversion scenarios must be investigated in order to explore different a priori models, data combinations, and stabilizers. It is important to use rigorous but fast 3D inversion methods. Our approach to this is based on iterative migration; theoretically equivalent to, but more efficient than iterative inversion. As we have demonstrated with our synthetic example for the Shtokman field, we are able to effectively invert multi-component, multi-frequency and multi-line CSEM surveys for models with millions of cells, making it practical to run multiple scenarios in order to build confidence in the robustness of features in the resistivity models, as well as to discriminate any artifacts that may arise from the interpretation of a single resistivity model. We have shown that reliance on regularization with smooth stabilizers will produce resistivity models that bear little resemblance to economic geology, while focusing stabilizers recover more realistic resistivity models with sharper geoelectric contrasts and converge to lower misfits in fewer iterations.

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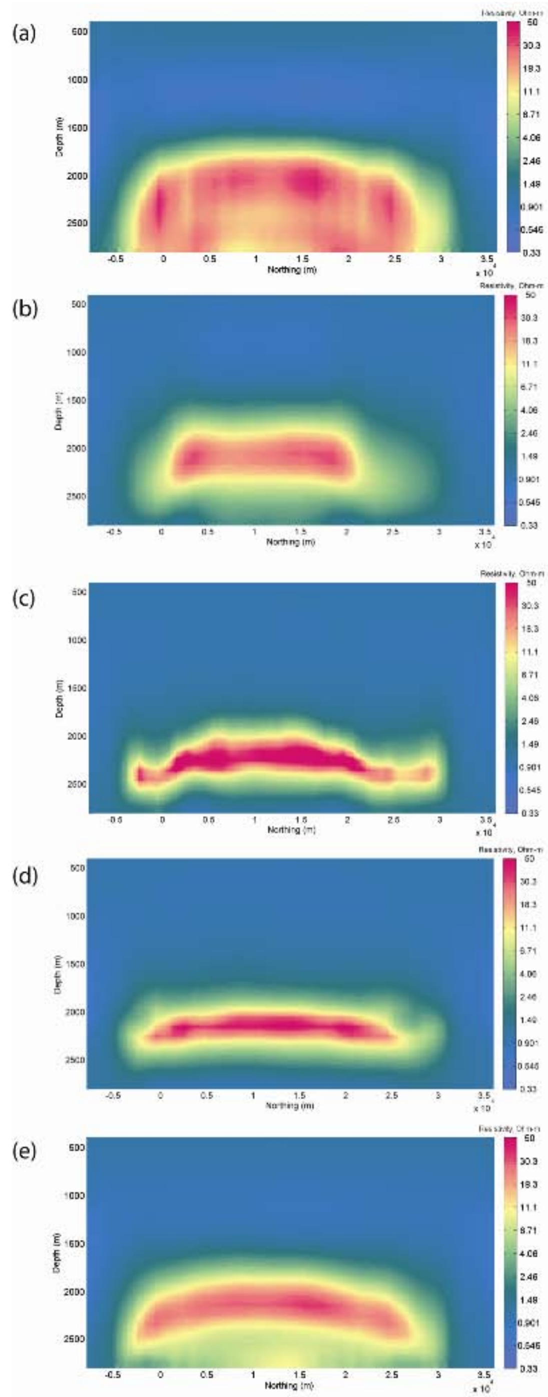

Figure 5. *Resistivity cross-sections obtained using (a) Occam, (b) minimum norm, (c) minimum support, (d) minimum vertical support, and (e) minimum gradient support stabilizers for migration of the inline electric field.*

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