

Exploring multiple 3D inversion scenarios for enhanced interpretation of marine CSEM data: an iterative migration analysis of the Shtokman gas field

Michael S. Zhdanov,^{1,3} Evgeny P. Velikhov,² Martin Čuma,^{1,3} Glenn Wilson,^{3*} Noel Black³ and Alexander Gribenko^{1,3} argue that the key to deriving a reliable quantitative interpretation from marine controlled-source electromagnetic (CSEM) data is through the integration of shared earth modelling and robust 3D CSEM inversion. An iterative migration method for CSEM data is presented that is equivalent to rigorous inversion, illustrated with a case study of the Shtokman gas field in the Barents Sea.

The premise of the various marine controlled-source electromagnetic (CSEM) methods is sensitivity to the lateral extents and thicknesses of resistive bodies embedded in conductive hosts. For this reason, CSEM methods were initially applied to de-risking exploration and appraisal with direct hydrocarbon indication. However, CSEM methods represent just part of an integrated exploration strategy. The value of CSEM data is only realized when it is integrated with sound geological understanding in a shared earth model. The most successful applications of CSEM to date have been in complement to those seismic interpretations where lithological or fluid variations cannot be adequately discriminated by seismic methods alone (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. CSEM interpretation is inherently reliant on iterative inversion methods since the data cannot simply be separated or transformed with linear operators as per seismic methods.

Three questions arise when we try to solve a geophysical inverse problem: 1) does a solution exist? 2) is the solution unique? and 3) is the solution stable? According to Hadamard (1902), a problem is ill-posed if the solution is not unique or if it is not a continuous function of the data (i.e., an arbitrarily large perturbation of the solution corresponds to a small perturbation of the data). This suggests the CSEM inverse problem is ill-posed because the solutions are either non-unique or unstable. However, there is an interesting historical background to the solution of this problem. During the Second World War, the Geophysical

Institute of the USSR Academy of Sciences commissioned Academician Andrei N. Tikhonov to conduct a mathematical evaluation of electrical prospecting methods. While doing so, he worked closely with geophysicists exploring for oil in the Ural Mountains. As a mathematician, Tikhonov believed that any attempt to recover the electrical properties of the Earth from observed resistivity data were at best limited and at worst, doomed to fail. To his surprise, the geophysicists were successful interpreting such data and discovered several large oil fields.

Tikhonov realized that by imposing their preconceived geological knowledge of the possible solutions, and then selecting the most geologically relevant models, the geophysicists were able to make valid interpretations. Based on this experience, Tikhonov formalized the following concept: intuitive estimations about the potential solutions are useful in selecting the class of models from which a solution is sought (Tikhonov, 1943). This concept became known as regularization and was central to the subsequent development of theories for solving ill-posed problems in applied mathematics (Tikhonov and Arsenin, 1977).

In 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. Most often, resistivity models are obtained from regularization with a smooth stabilizing functional. This means the first or second derivatives of the resistivity distribution are minimized, resulting in smooth distributions of the resistivity. This type of solution allegedly satisfies Occam's razor since it is claimed to produce the most 'simplistic' model for the data. Unfortunately, this

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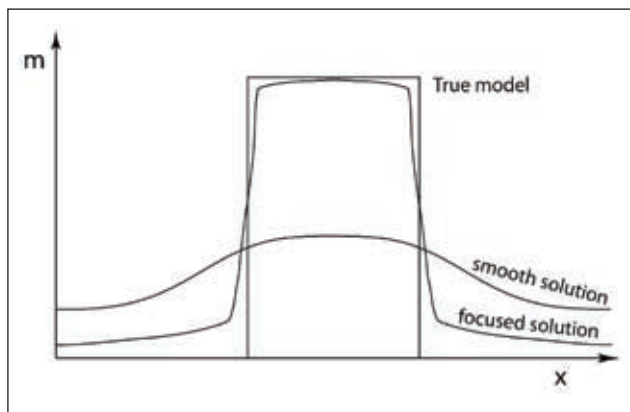


Figure 1 A smooth stabilizer will recover a model with a smooth distribution of model parameters. A focusing stabilizer will recover a model with sharper boundaries and contrasts, and will be closer to the true model.

approach has led to a tendency to deliver the single resistivity model as ‘the’ solution. Moreover, this approach is the least relevant to economic geology, which is anything but smooth. When the resistivity distribution is discontinuous, smooth stabilizers can also produce spurious oscillations and artifacts. Therefore, a model that is smooth in the first or second derivative of the anomalous resistivity distribution is not any ‘simpler’ than, say, a model that has the minimum

volume of the anomalous resistivity distribution. As we will show, the use of focusing stabilizers allows us to recover stable and geologically realistic models with sharper geoelectric boundaries and contrasts (Figure 1).

In this paper, we intend to demonstrate that best practice is to run multiple inversion scenarios in order to enable interpreters to explore alternative resistivity models and select the most geologically plausible ones. Such practice identifies any artifacts that may arise from interpreting a single resistivity model. Alternative models may be used to reveal which additional data, if any, are needed to further constrain the interpretation. To this end, it is important to develop rigorous but fast 3D inversion methods. The requirement for ‘fast’ 3D inversion makes the various stochastic methods computationally prohibitive. Rigorous inversion methods are also not practical, as the sensitivity matrix needs to be constructed at each iteration for the many transmitter-receiver combinations in a CSEM survey. To minimize computation costs, various incarnations of the Born approximation which linearize the adjoint operators are often used. However, such approximations result in inaccurate calculations of the gradient directions, model updates, and thus final models.

Our more pragmatic approach is based on iterative electromagnetic migration. Iterative migration is implemented in a reweighted regularized conjugate gradient method to

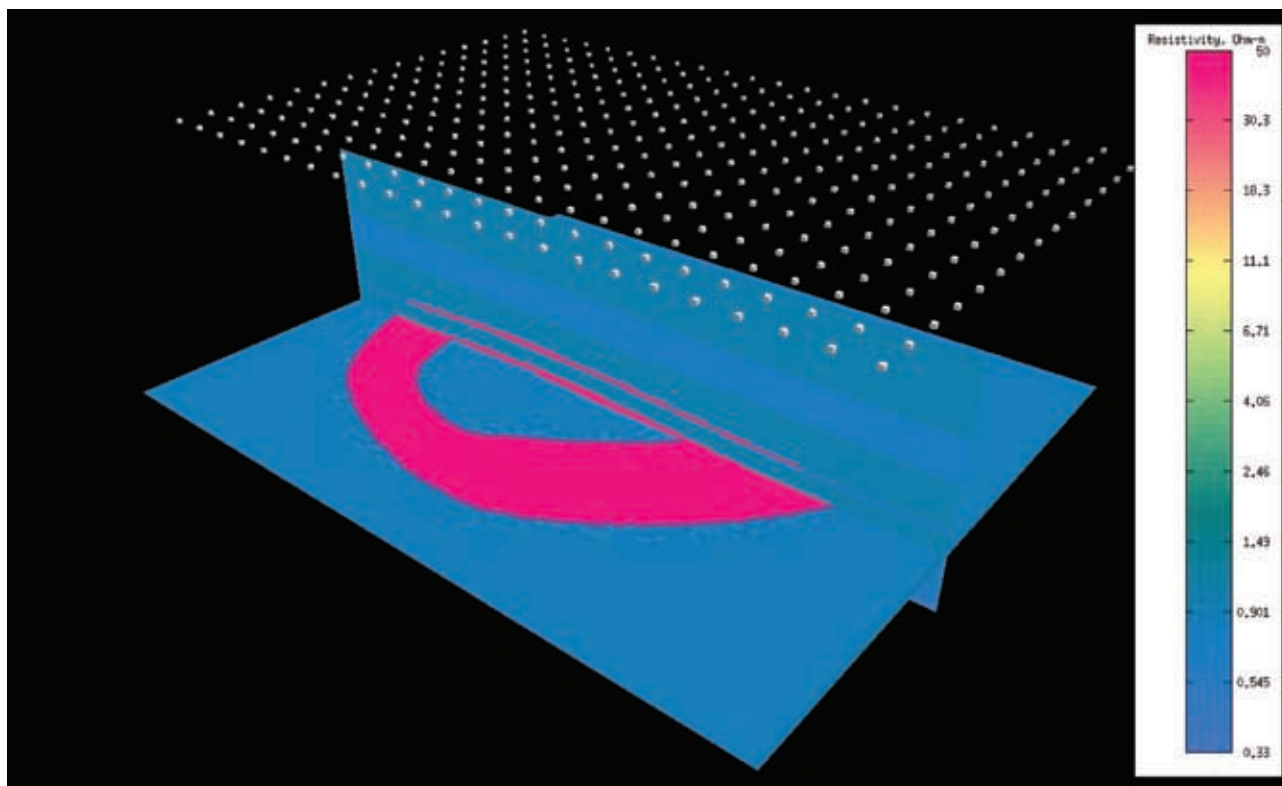


Figure 2 3D view of the Shtokman resistivity model, with three of the four reservoir units shown. The vertical cross-section corresponds to those vertical cross-sections shown in Figures 3, 4, and 5. The horizontal cross-section shows the extent of the main reservoir horizon. Receiver positions are denoted by the grey cubes. A vertical exaggeration of six was used in this image.

rigorously compute the gradient directions without needing to explicitly construct the sensitivity matrix or its products. The modelling is based on the 3D integral equation method with inhomogeneous background conductivity that can capture arbitrary geological complexity. We have implemented our iterative migration method in a fully parallelized code that allows us to invert entire 3D CSEM surveys for models with millions of cells. Our approach makes it practical to run multiple inversion scenarios as described above, and as we shall demonstrate in our Shtokman feasibility study.

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 evaluation of adjoint operators. When applied iteratively, migration is analogous to inversion in providing a rigorous solution to the corresponding inverse problem (Zhdanov, 2002, 2009).

At each iteration, we calculate the predicted fields measured at the receiver positions due to a 3D resistivity model. We minimize the computational burden for CSEM surveys by exploiting the reciprocity theorem and by interchanging the assignment between transmitters and receivers. The receivers become sources and the transmitters become receivers. We then calculate the residual fields as the difference between the observed and predicted data. These residual fields are then migrated. This means the residual fields are used as source moments and these are simultaneously solved to compute the adjoint operator. 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 conventional principles of regularization theory. The process is then repeated until the misfit reaches a preset threshold, or the maximum number of iterations is reached (Zhdanov and Čuma, 2009; Zhdanov et al., 2010). The described approach allows us to use the physical properties of the migration field in order to construct effective numerical methods for computing the gradient. Thus, when applied iteratively, migration is equivalent to inversion. The main difference between migration and inversion is in the physical interpretation of the gradient directions.

The reweighted regularized conjugate gradient method is used as the basis for iterative migration. The user has the option to regularize the migration with a choice of stabilizing functional, as will be discussed in the next section. The modelling is based on the 3D integral equation method with inhomogeneous background conductivity (Endo et

al., 2009), which enables models with arbitrary geoelectric complexity to be migrated. Our modelling exploits the Toeplitz structure of the large, dense matrix system in order to solve multiple right-hand side source vectors using an iterative method with fast matrix-vector multiplications provided by a 2D FFT convolution. This algorithm reduces storage and complexity, and naturally lends itself to parallelization. Another advantage of this approach is that once the inhomogeneous background fields and Green's tensors have been pre-computed, they are stored and re-used in subsequent iterations and different migrations, further reducing runtime. Modelling in the frequency-domain has two additional advantages over time-domain methods. First, the effects of frequency-dependent complex conductivity which occurs in induced polarization can be modelled. Secondly, artificial dispersion effects that arise when time-stepping in direct time-domain modelling are avoided.

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. Using an inappropriate type of stabilizer is akin to looking for an inappropriate solution. In this section, we will briefly describe different smooth and focusing stabilizers in order to demonstrate the results from the iterative migration of the same CSEM data produced by each.

A minimum norm (MN) stabilizer will seek to minimize the norm of the difference between the current model and an a priori model:

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

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

$$S_{oc}(m) = \int_V (\nabla m - \nabla m_{apr})^2 dv,$$

and produces smooth resistivity models that bear little resemblance to economic geology. Moreover, it can result in spurious oscillations and artifacts when the resistivity is discontinuous. Alternatively, the use of focusing stabilizers

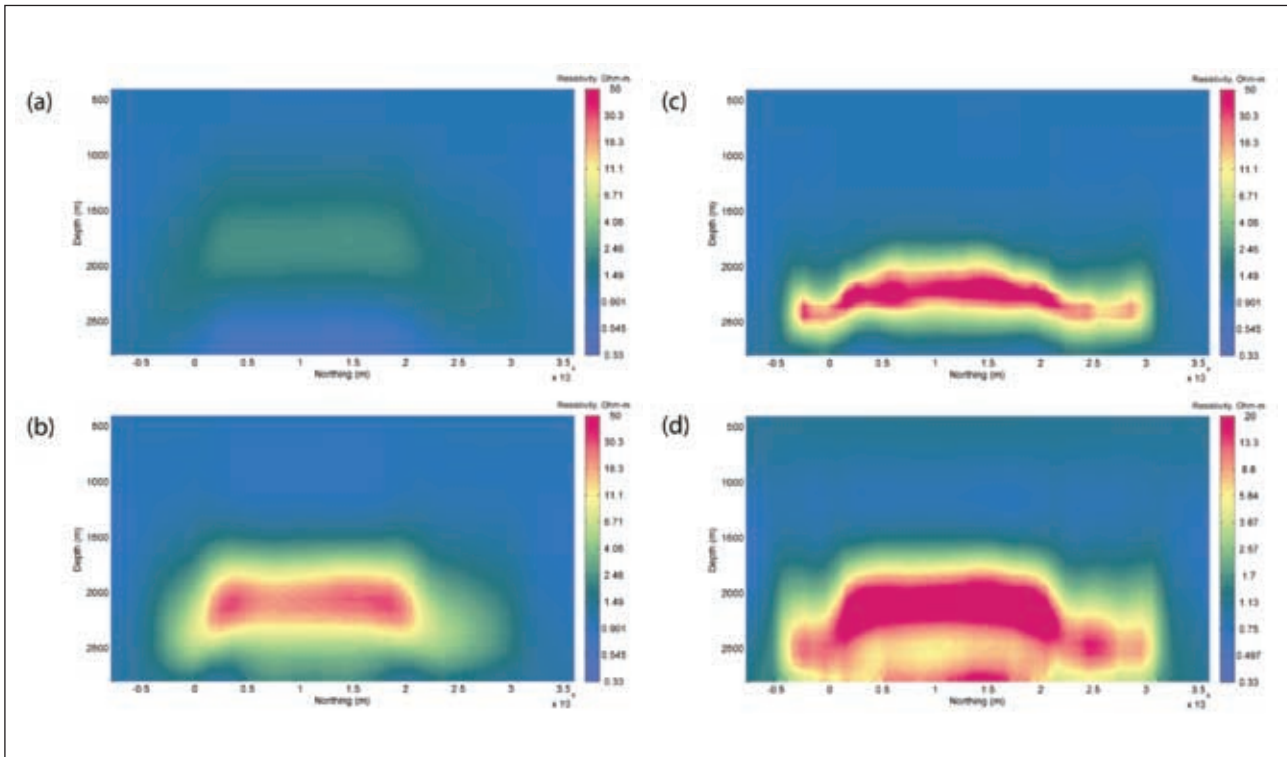


Figure 3 Vertical cross-section of the Shtokman resistivity model obtained from the iterative migration of inline electric field data using the following stabilizers: (a) Occam, (b) minimum norm, (c) minimum support, and (d) minimum gradient support.

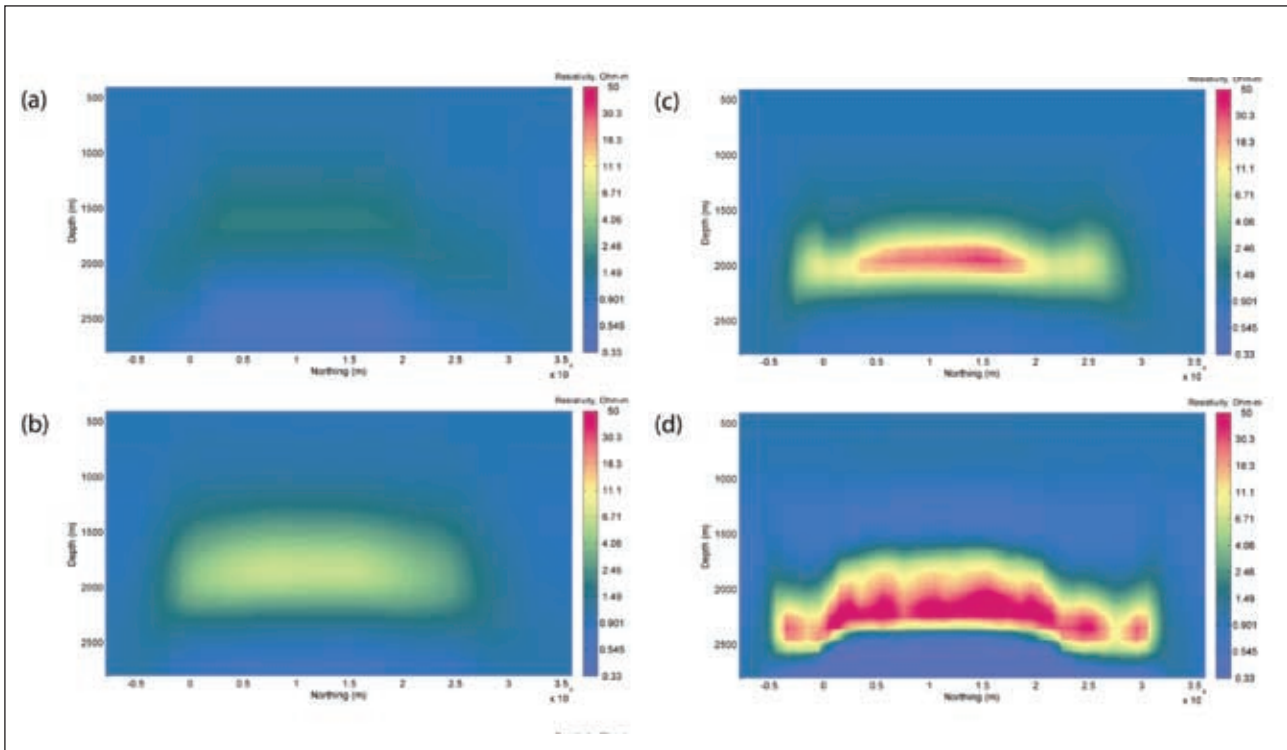


Figure 4 Vertical cross-section of the Shtokman resistivity model obtained from the iterative migration of inline electric and transverse magnetic field data using the following stabilizers: (a) Occam, (b) minimum norm, (c) minimum support, and (d) minimum gradient support.

makes it possible to recover models with sharper geoelectric boundaries and contrasts. We briefly describe this recently introduced family of stabilizers here and refer the reader to Zhdanov (2002, 2009) for further details.

First, we present the minimum support (MS) stabilizer:

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

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. A focused distribution of the model parameters is penalized less. Similarly, 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, approximately 500 km north of the Kola Peninsula. It is currently operated by a joint venture between Gazprom, Total, and StatoilHydro. Shtokman 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 (Gazprom, 2009). The water depth gently varies between 320 m and 340 m over the field. The overburden sequence contains Jurassic and Cretaceous siliciclastics of shallow marine origin. From approximately 1800 m depth, the Shtokman reservoir sequence consists of four Middle and Upper Jurassic sandstone horizons. The gas is trapped in an anticlinal four-way dip structure that is faulted in the crest. The reservoir horizons vary from 10 m to 80 m thickness. They have porosity between 15% and 20% and permeability ranges from hundreds of millidarcies to over a darcy (Zakharov and Yunov, 1995). We constructed a 3D geoelectric model of the Shtokman field from available geological and geophysical information. This model was used to simulate a multi-frequency 3D CSEM survey at 0.25 Hz, 0.5 Hz, and 0.75 Hz using the 3D integral equation method. The survey consisted of 345 receiver positions distributed over a 2 km x 2 km grid draped over the seafloor (Figure 2). The transmitter was towed 50 m above the sea floor along 50 km long lines that were spaced 2 km apart.

A number of migration scenarios were considered. In each, the migration domain was 44 km x 40 km x 3 km in easting, northing, and depth. For the entire survey, we

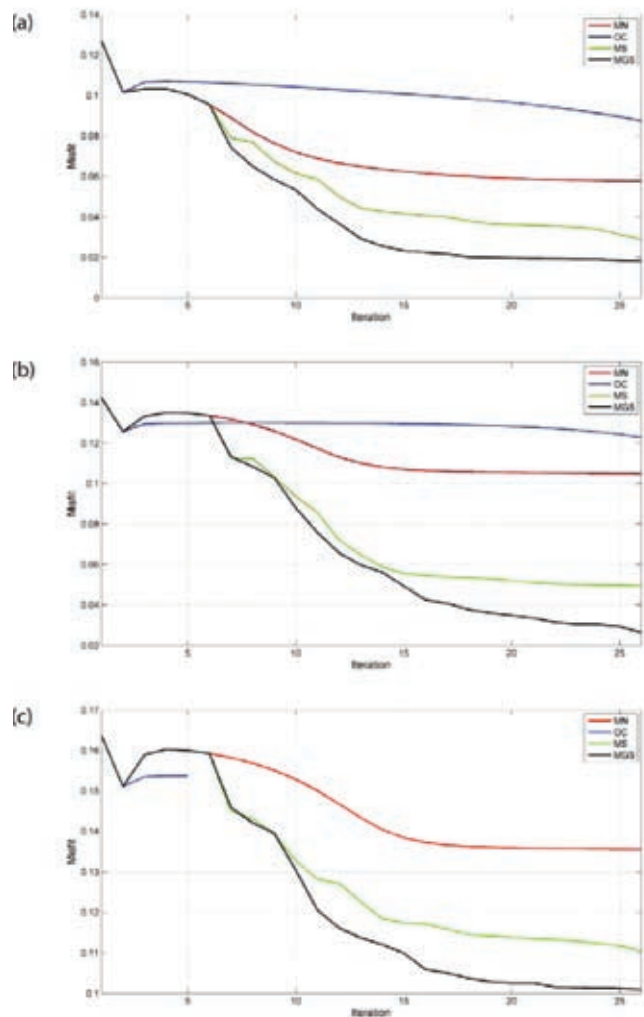


Figure 6 Convergence of the misfit for the following stabilizers: Occam (OC), minimum norm (MN), minimum support (MS) and minimum gradient support (MGS). These convergence curves are shown for the (a) iterative migration of the inline electric fields, (b) joint iterative migration of the inline electric and transverse magnetic fields, and (c) joint iterative migration of the inline and vertical electric and transverse magnetic fields.

prepared different combinations of the multi-frequency data for migration: inline electric field only, inline electric and transverse magnetic fields, and 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, and minimum gradient support. For the purpose of benchmarking performance, all scenarios were run for a maximum of 26 iterations rather than a misfit tolerance. Moreover, all scenarios commenced with no a priori models so as to not bias the effectiveness of any stabilizer. With no a priori model, 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

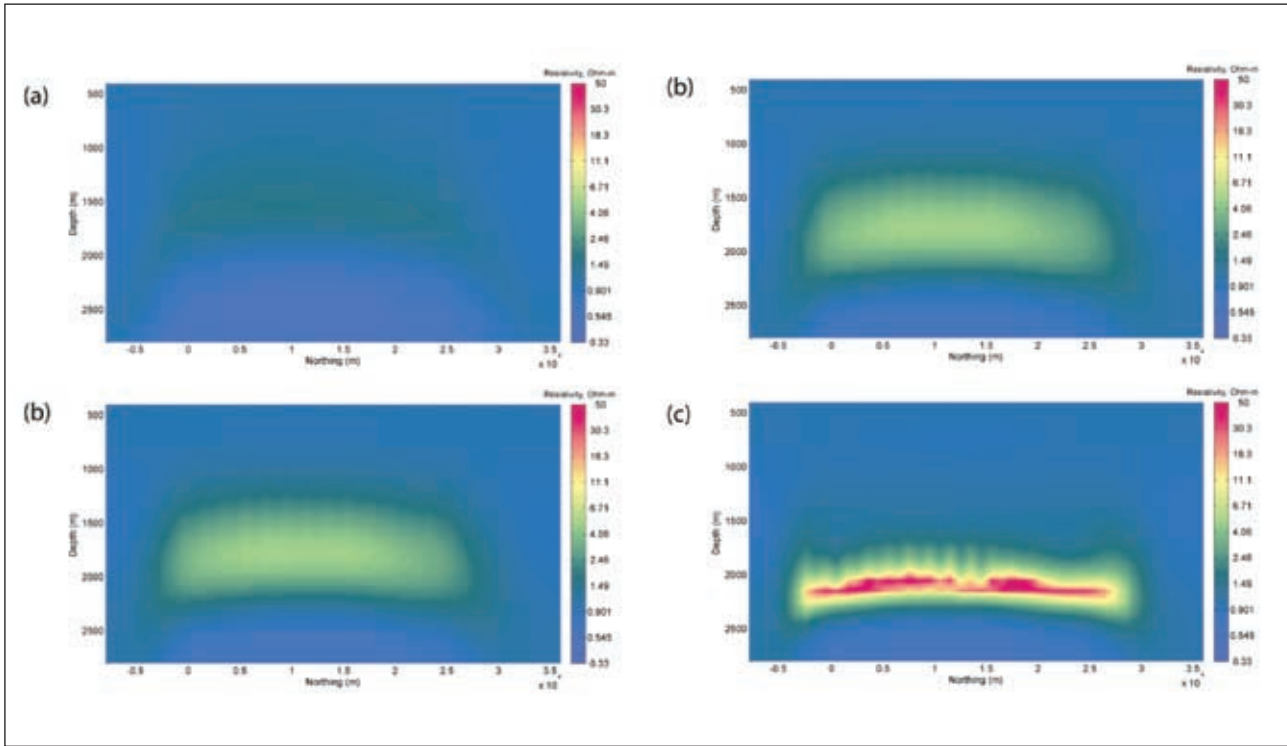


Figure 5 Vertical cross-section of the Shtokman resistivity model obtained from the iterative migration of inline and vertical electric and transverse magnetic field data using the following stabilizers: (a) Occam, (b) minimum norm, (c) minimum support, and (d) minimum gradient support.

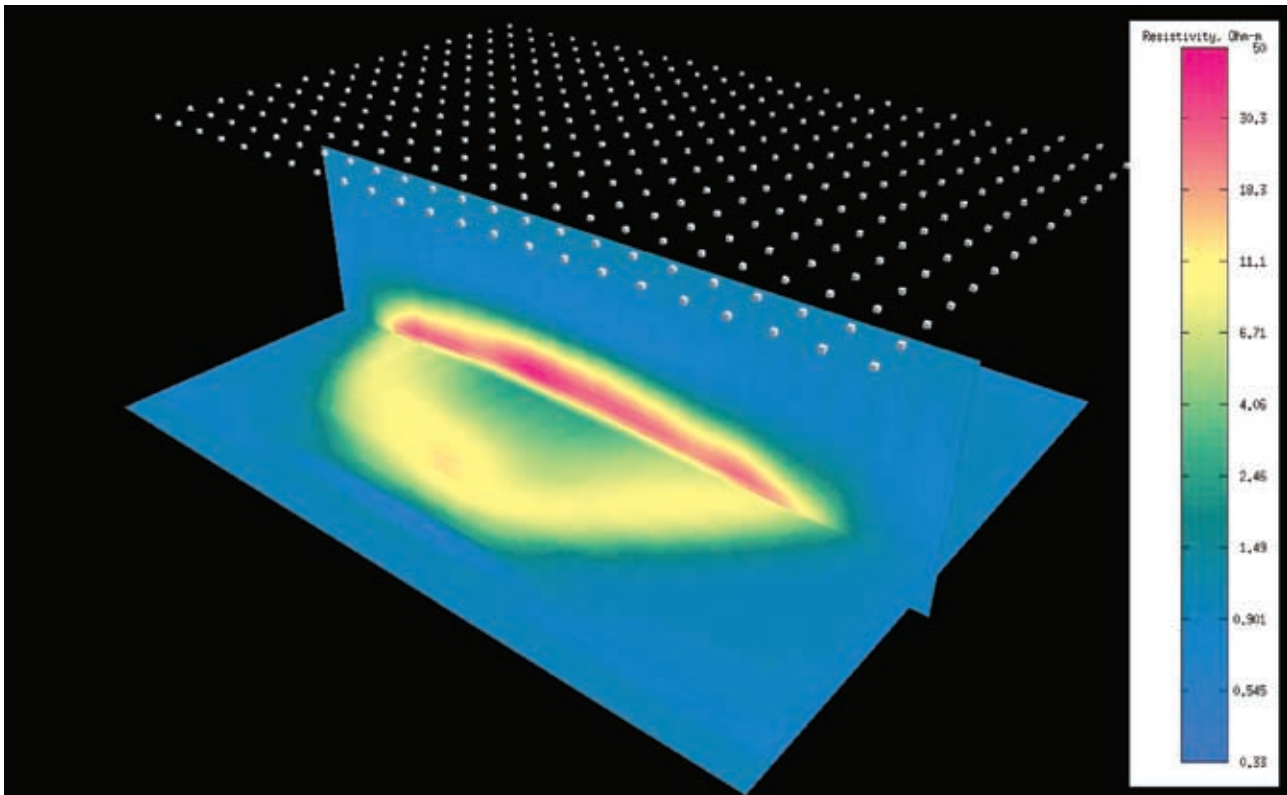


Figure 7 3D view of the Shtokman resistivity model obtained from the joint iterative migration of the inline and vertical electric and transverse magnetic fields using the minimum gradient support stabilizer. The cross-sections are corresponds to the cross-sections shown in Figure 2. The horizontal cross-section shows the extent of the main reservoir horizon. Receiver positions are denoted by the grey cubes. A vertical exaggeration of six was used in this image.

with a general shape and conductivity-thickness product that is comparable to the stacked reservoir units. This is a well known limitation of the CSEM method's resolution.

Figures 3 to 5 present the results for the different migration scenarios at their final iterations. Though the actual resistivity models are 3D, we only show vertical cross-sections through each model for ease of visual inspection of model quality. Figures 3 to 5 show that migration with the Occam stabilizer converged to produce very smooth resistivity models 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 or under-estimating as ones produced with the Occam stabilizer. Models with sharper geoelectric boundaries and contrasts were obtained using the family of focusing stabilizers. Migration with the minimum support and minimum gradient support stabilizers produced compact resistivity models. These resistivity models bear the most geological relevance to the actual geology as they recovered the anticlinal trends of the Shtokman reservoir units (Figure 6).

Next, we compared the convergence of the misfit, which we define as the norm of difference between the normalized observed and predicted data (Figure 7). For each scenario, the family of focusing stabilizers had similar near-quadratic convergence to lower misfits. We notice that migration with the Occam stabilizer had the slowest convergence. In other words, focusing stabilizers produce better results in less time compared to smooth stabilizers. Our results also show that there is 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. It follows that as the industry moves towards acquiring 3D surveys with the intent of defining 3D structure, the ability to invert all components of data along multiple lines for 3D resistivity models will prove to be essential.

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. For such practicality, 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. We have implemented this method in a fully parallelized code. 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. This makes 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 (if any) resemblance to economic geology. We have shown that focusing stabilizers recover more realistic resistivity models with sharper geoelectric contrasts and converge to lower misfits in fewer iterations.

Acknowledgements

The authors acknowledge TechnoImaging for support of this research and permission to publish the results. Zhdanov, Čuma and Gribenko also acknowledge the support of The University of Utah's Consortium for Electromagnetic Modeling and Inversion (CEMI) and Center for High Performance Computing (CHPC).

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