Some results from ModEM3DMT, the freely available OSU 3D MT inversion code

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SUMMARY

At the 3DEM-5 workshop in 2013, we presented a paper entitled "ModEM: developing 3D EM inversion for the masses", outlining our then recent development of a modular system for inversion of EM geophysical data, called ModEM. As promised in that presentation, we made a version of the code that is suitable for 3D modeling and inversion of magnetotelluric data freely available for academic use shortly thereafter. There are now over 250 registered users, of ModEM3DMT from around the globe. To date at least 50 publications cite use of ModEM for 3D inversion of real MT datasets to address diverse problems in applied and basic Earth Science research at a range of scales. Here we present an overview of some of these results, focusing on studies that the authors have been involved in, and are thus most familiar to us.

Keywords: Magnetotellurics, inversion, case study

INTRODUCTION

Interpretation of electromagnetic (EM) data underwent a revolution in the late 1980's, when computer codes for two-dimensional (2-D) inversion first became widely available. Over the next decade, the EM induction community learned how to use these new tools and to make scientifically defensible interpretations of, for example, magnetotelluric (MT) profile data, greatly enhancing the impact of EM methods in the broader field of Earth science. We are now in the midst of a potentially more profound revolution, with the transition to larger and denser datasets and fully 3-D inversion and interpretation. The revolution is being driven by development of cheaper (and easier to use) digital instruments, improved data acquisition strategies, increasingly powerful computers, and software that has made 3-D inversion practical, if not routine. Because some of this software is relatively freely available, one no longer has to be (or even work with) a specialist in numerical methods to do 3D interpretation of real datasets.

"ModEM" was developed at Oregon State University as a modular system for inversion of EM geophysical data (Egbert and Kelbert, 2012; Kelbert et al., 2014). Although designed for more general (frequency domain) EM applications, and intended as a testbed for exploring inversion search and regularization strategies, our own initial uses of ModEM were for 3-D imaging of the deep crust and upper mantle at large scales. Since 2013 we have offered a version of the code suitable for 3D MT inversion on an "as is, user beware" basis for free for non-commercial applications. This version, which we refer to as ModEM3DMT, has since been widely used by the international MT community. Over 250 users have registered to download the source code. At least 50 MT studies in the refereed literature, covering locations around the globe at a range of spatial scales, cite use of ModEM for 3D inversion. In this presentation, we will provide an illustrative sample of some of the results from these studies, and briefly consider some of the general lessons learned. We focus on some of our own work, inverting long-period MT data in the continental USA, but as space permits, we show also some results from other regions and at smaller scales.

ModEM

The mathematical development of Egbert and Kelbert (2012) provides the framework for implementation of ModEM as a general modular system for inversion of frequency-domain EM data. ModEM is written in Fortran 95 following an object oriented programming philosophy, and consists of interchangeable modules which in principal can support different inversion algorithms, forward modelling codes, data functionals, model parameterization and regularization, etc., to allow relatively painless implementation of applications for inversion of a broad range of EM geophysical data types. A coarse-grained parallelization (over forward/adjoint problems, using MPI) has been incorporated following the approach described by Meqbel (2009). The parallelization is largely independent of the specifics of the forward solver and inversion search algorithm.

Non-linear conjugate gradients (NLCG) is the default search algorithm for ModEM3DMT, although a data-space conjugate gradients scheme (Siripunvaraporn and Egbert, 2007) is also available as an option. Forward modelling is based on a 3-D finite-difference staggered-grid electric field solver similar to that of

Siripunvaraporn et al., (2005). All of the standard MT

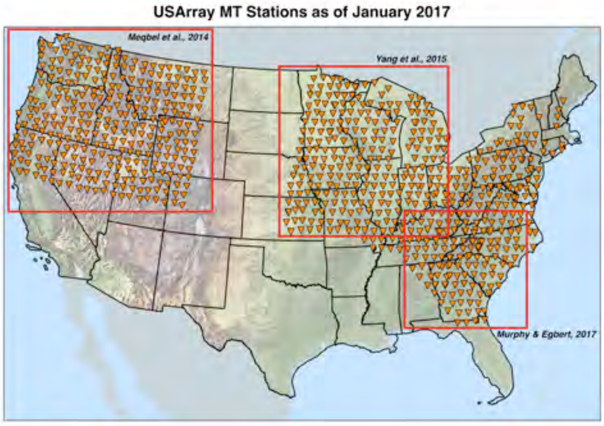


Figure 1. Map of long period MT sites collected as part of the EarthScope USArray MT campaign. Here we present selected results from 3D inversions from data in each of the three boxes.

transfer functions (including inter-station transfer functions) are supported. It is simple to add new data types—for example, phase tensors have been added (Tietze et al., 2015). A simple model parameterization has been used, with each cell in the numerical grid treated as an independent parameter, and the inversion has been regularized by penalizing deviations from a prior, with smoothness enforced using a model covariance, as in Siripunvaraporn and Egbert (2000). In our current implementation, the covariance allows parts of the model space to be "frozen", specification of discontinuities across flat or sloping interfaces, and spatially variable covariance length scales.

Some Results: EarthScope

Here we present a sampling of results that have been obtained from inversion of data from the EarthScope USArray project, which has been collecting high-quality long period (10-10,000s) MT data covering much of the continental US over the past decade (Kelbert et al., 2011; see Fig. 1 for the present coverage). The data aquisition strategy, covering large areas with relatively uniform, but wide (70 km), site spacing is nearly ideal for imaging deep-crust to uppermost mantle electrical structure. The three-dimensional images resulting from application of ModEM to large subsets of these MT data (as defined by boxes in Fig. 1) provide an exciting new view of the large-scale electrical structure of North America (Meqbel et al., 2014; Yang et al., 2015; Murphy and Egbert, 2017). Some key points from these studies are highlighted in the captions to Figs. 2-5. In our presentation we will expand our discussion to sample from a broader set of published results that have been obtained with ModEM, with an ongoing slide show to allow snapshots and renderings from a larger number of studies attacking a range of problems.

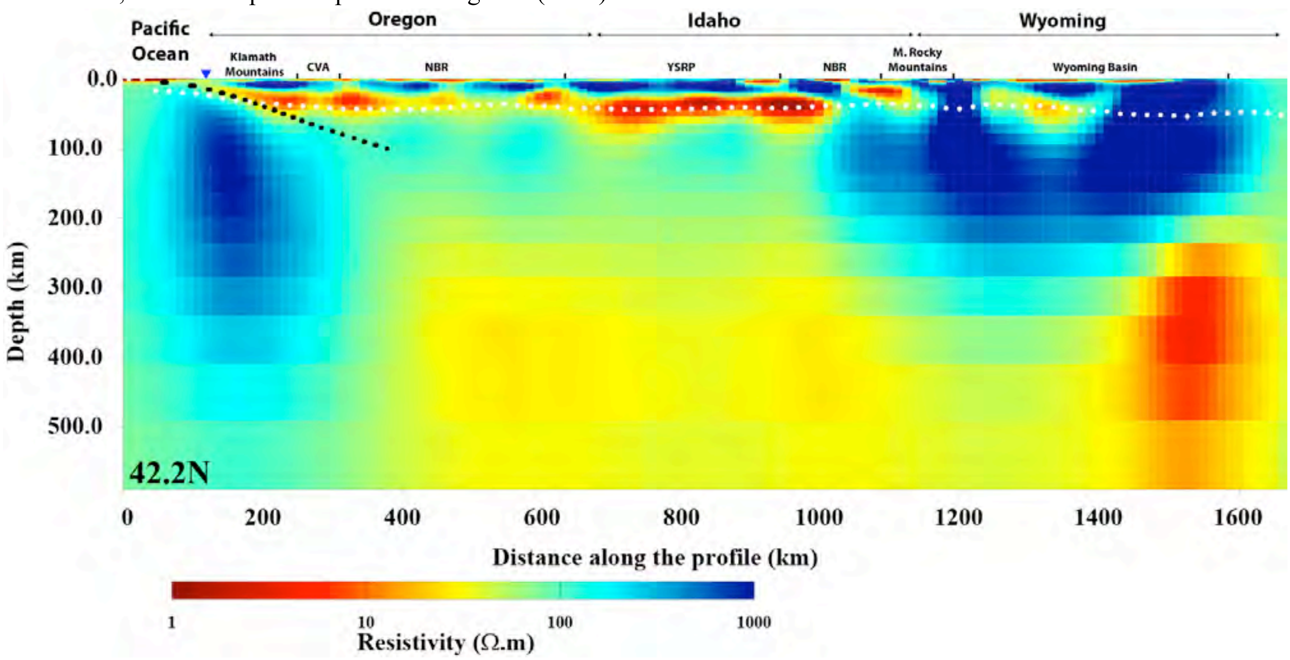


Figure 2. Cross-section through the Pacific Northwest (PNW) EarthScope model of Meqbel et al. (2014) at a latitude of 42.5 N. Key features to note: resistive oceanic lithosphere on the western edge of the profile; high conductivities near the moho (dashed white line) beneath the Klamath Mountains, Northwest Basin and Range (NBR), Yellowstone-Snake River plain (YSRP); deep (> 200 km) resistive Wyoming Craton; moderately high aesthenospheric conductivities. Note that the lithosphere-aesthenosphere boundary (LAB) is very shallow beneath the NBR. Analysis of lab results suggests that the conductivities at ~100km depth in this area are consistent with a nearly dry upper mantle. At greater depth, modest hydration (a few hundred ppm) is required.

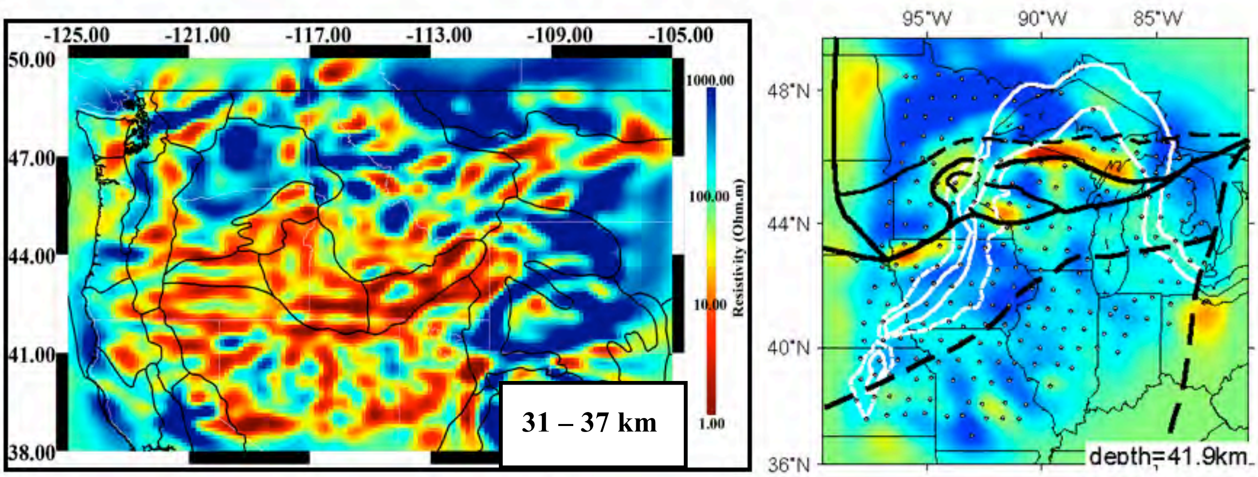
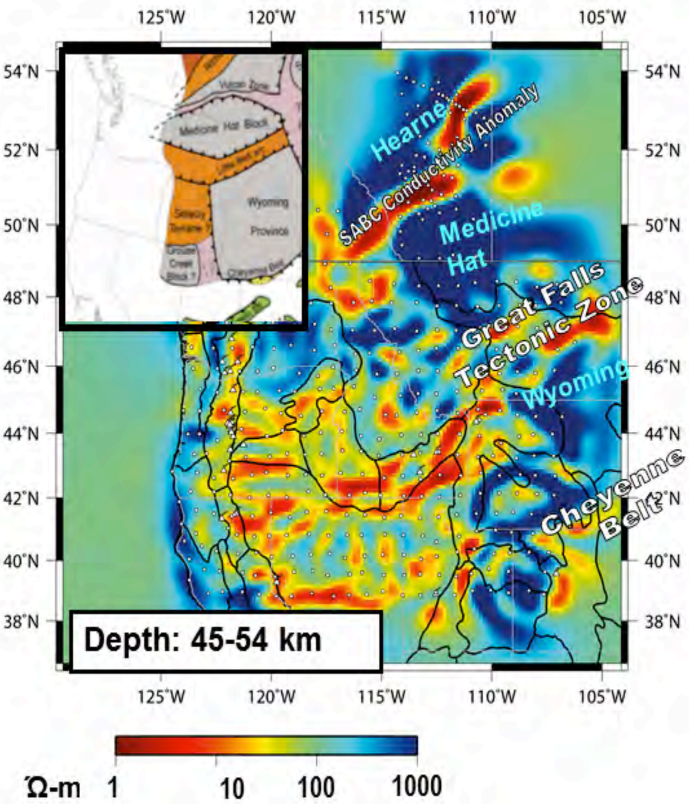


Figure 3. Depth-sections (both near the moho) for the EarthScope model of (left) Meqbel et al. (2014), and (right) the mid-continent model of Yang et al. (2015). In the tectonically active parts of the west (Basin and Range, Snake River Plain, Cascade Arc) high conductivities in the lower crust and uppermost mantle are ubiquitous. The mid-continent (right) has been quiescent for over 1 Ga, and generally is resistive at similar depths. This provides clear evidence that the lower crustal conductive layers in the west are a transient feature, associated with magmatic fluids that were formed as a result of slab dehydration in the Cascadia subduction zone. The isolated areas of high conductivity in the lower crust can be associated with ancient (~1.8 Ga) sutures, and are most likely the result of interconnected graphite and/or sulfides. As discussed further in Fig. 4, some of the conductive features in the west at this depth are likely also the signature of ancient sutures.



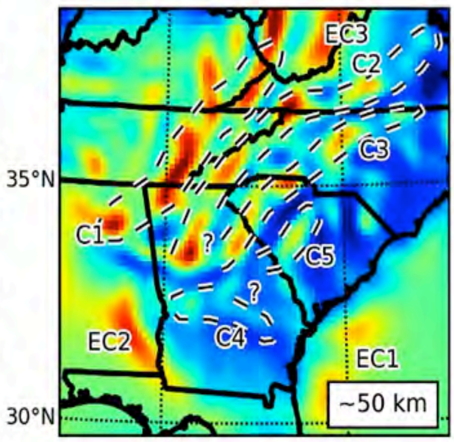


Figure 4. Depth-sections for the (left) PNW model, and (right) the Eastern N.A model of Murphy and Egbert (2017). In both areas (and in the mid-continent as seen in the right panel of Fig.3) elongated conductive features are aligned with ancient suture zones (e.g., dashed outlines) that extend through the crust and into the upper mantle lithosphere.

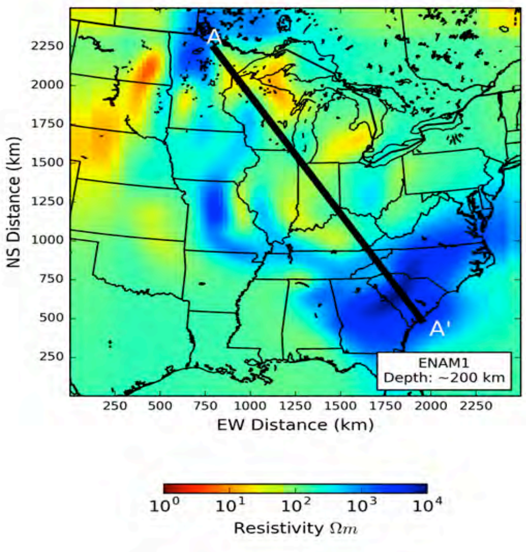


Figure 5. A preliminary large-scale model covering the two eastern boxes shown in Fig. 1. The lithosphere east of the modern Appalachian front is remarkably resistive, and thick (comparable to the Superior Craton, in the far northwest of this model; Murphy and Egbert, 2017).

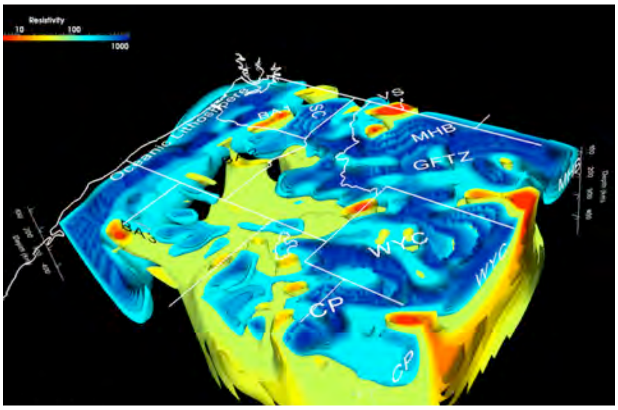


Figure 6. A 3D view of the PNW EarthScope model of Meqbel et al. (2014).

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