Large-scale 3D inversion of EarthScope MT data from the area surrounding Yellowstone National Park

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Summary

We have developed an efficient method for large-scale 3D magnetotelluric (MT) inversion which addresses two common problems associated with 3D MT inversion: computational time and memory requirements. In order to minimize computational time, our modeling is based on a parallel implementation of the integral equation method. To minimize memory requirements, we have implemented a receiver footprint which dramatically reduces the memory needed for storing Fréchet derivatives for large 3D models. We have applied our 3D MT inversion methodology to EarthScope data acquired over the western United States. In this paper, we present the 3D earth models of the upper mantle beneath Yellowstone National Park as independently revealed by both 3D MT inversion and 3D seismic tomography. These earth models show a highly conductive region associated with the plume of hot material rising from the mantle towards the Yellowstone volcano. The plume is identified as a west-dipping conductive structure in the 3D conductivity model of geometry similar to the low velocity structure in the 3D P-wave velocity model.

Introduction

EarthScope is a National Science Foundation program designed to explore the structure and evolution of the North American continent, and to further understand the processes controlling earthquakes and volcanoes. A major part of the EarthScope project is the USArray of seismic, magnetotelluric, and geodetic instruments that are being deployed over the next decade across the conterminous United States. This transportable array provides an unparalleled means to study the geology of the United States through seismology and magnetotelluric data. EMScope is the magnetotelluric (MT) component of the USArray program, managed by Oregon State University on behalf of Incorporated Research Institutions for Seismology (IRIS). EMScope comprises long-period investigations at hundreds of sites in the continental United States, in addition to a number of long-period backbone stations. By mid-2010, MT data had been collected at about 250 stations located throughout Oregon, Washington, Idaho, northern California, most of Wyoming and Montana, and large sections of Nevada.

The unique geological setting of the western United States, including plate boundary transform faulting, subduction, intra-plate extension of the Basin Range and the active Yellowstone hotspot, is very important both for the study of its geodynamic history and for understanding the physical processes controlling earthquakes and volcanic eruptions (e.g., Bishop, 2003). It is a tectonically active region with the subducting Juan de Fuca and Gorda plates, and volcanically important from the effects of the North American Plate moving over a mantle plume currently located beneath Yellowstone National Park. For such a complex region, definitive structural interpretations based purely on seismological observations are not sufficient for more comprehensive study of the deep earth interior. Conductivity in the subsurface plays a significant role in determining tectonic activities principally because of its sensitivity to temperature; the presence of interstitial fluids, melts, and volatiles; and bulk composition.

Yellowstone is an example of a continental hotspot that is located 1,600 km east of the western North American plate boundary. While most of Earth's volcanism is associated with plate boundaries, including mid-ocean ridges and subduction zones, the Yellowstone hotspot occurs within a continental plate and it resulted from a mantle plume interacting with the overriding North America plate. In traditional geologic thinking, such plumes ascend vertically from the core-mantle boundary to the base of the lithosphere (e.g., Morgan, 1971). However, new models (e.g., Steinberger et al., 2004) predict that plumes can rise upward along curved paths following the directions of convective mantle flow and may not necessarily have a core-mantle boundary source. Thus, hotspots are not necessarily fixed, and horizontal mantle flow can deflect and tilt a plume. Until recently, plumes have not been reliably imaged by geophysical methods. Smith et al. (2009) presented one of the first P-wave velocity models of the upper mantle beneath the Yellowstone hotspot area. These data revealed a well defined low-velocity body from ~80 to ~250 km directly under the Yellowstone caldera and from ~80 to ~200 km beneath the eastern Snake River Plain, and a ~60° west-tilted low-velocity body from ~200 to ~650 km as a plume of partial melt that extends upward from the bottom of the mantle transition zone.

Large-scale 3D MT inversion of EarthScope data

Large-scale 3D MT inversion

Two major problems are commonly encountered in 3D MT inversion: computational time, and memory requirements. The former relates to modeling of the predicted data, and the latter relates to storage of the adjoint problem solutions required for gradient-type methods. To minimize computational time, our modelling is based on a parallel implementation of the integral equation method (Zhdanov, 2009). To minimize memory requirements, we have implemented a receiver footprint which dramatically reduces the memory needed for storing adjoint problem solutions. This allows us to invert MT data to 3D models discretized with more cells than would be possible with conventional 3D MT inversion. We have implemented this in a regularized re-weighted conjugate gradient method with focusing stabilizers (Zhdanov et al., 2010, 2011).

Figure 1. *Map of EarthScope MT stations deployed across Idaho, Montana, and Wyoming, encompassing Yellowstone National Park.*

Figure 1 presents a map of the western United States with the locations of the EarthScope MT stations collected in 2009 over Montana, Idaho, and Wyoming (shown by red dots). It is important to notice that the Yellowstone hotspot is located in the center of this area. First, we inverted MT data from 115 MT stations. The 3D inversion domain was spanned 900 km, 850 km, and 550 km in Easting, Northing, and depth respectively. We used cells with a horizontal discretization of 5 km by 5 km, with vertical cell sizes varying from 1 km at the surface and increasing logarithmically with depth. The 3D model contained a total of 1,958,400 cells. The initial model was selected as a uniform 75 Ωm half-space. Inversion was run for 32 iterations with a 450 km footprint, after which the normalized misfit between the observed and predicted MT data decreased to 7%. Figure 2 shows the 3D inversion result from this continental-scale MT survey. The distinguishing feature of our 3D resistivity model is a large, dipping conductive body which we interpret to be associated with a plume of hot conductive material in the upper mantle.

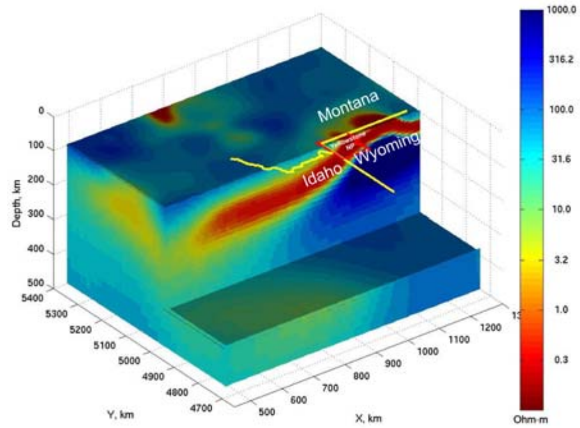

Figure 2. *A 3D resistivity model obtained from 3D inversion of EarthScope data acquired over Idaho, Montana, and Wyoming. The Yellowstone National Park boundary is shown by the yellow polygon.*

Next, we focused our attention on the area surrounding Yellowstone National Park and selected 28 MT stations from and around this area (Figure 3). In this case, the 3D inversion domain spanned 450 km, 400 km, and 550 km in Easting, Northing, and depth, respectively. Again, we used cells with a horizontal discretization of 5 km by 5 km, with vertical cell sizes varying from 1 km at the surface and increasing logarithmically with depth. The 3D model contained a total of 921,600 cells. The initial model was selected, as above, as an 75 Ωm half-space. Inversion was run for 40 iterations with no footprint, and the normalized misfit between the observed and predicted MT data decreased to 6%. An example of the observed and predicted data is shown in Figure 4.

Figure 3. *Map of EarthScope MT stations deployed across Yellowstone National Park.*

Large-scale 3D MT inversion of EarthScope data

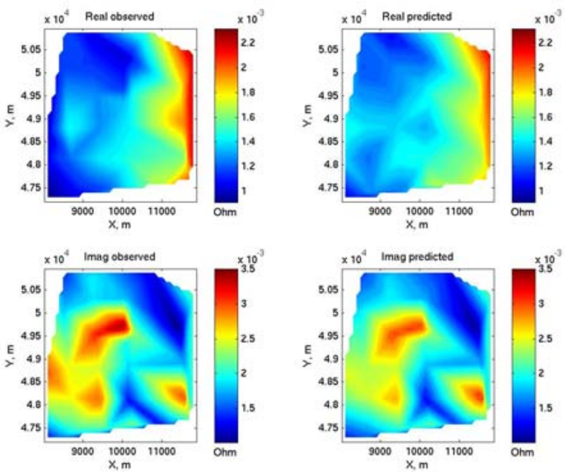

Figure 4. *Maps of the observed and predicted real parts of the principal impedances Z_{xy} (top panels) and the observed and predicted real parts of the principal impedances Z_{xy} (bottom panels) at 0.0097 Hz.*

Figure 5 shows a perspective view of the 3D conductivity model recovered from the 3D MT inversion. One can clearly see a plume of conductive hot mantle rising from the mantle transition zone at a depth of ~300 km to ~400 km. For a comparison, in Figure 6, we show the same perspective view of the 3D P-wave velocity model produced from seismic tomography by Smith et al. (2009). One can observe remarkable similarity of the images of the Yellowstone plume produced independently by seismic tomography and 3D MT inversion. The conductive body identified in the conductivity image is west-dipping in a similar way to the low-velocity body shown in the P-wave seismic tomography image. Taking into account the different physical nature of the P-wave velocity and conductivity anomalies, one should not expect that these two images would coincide completely. However, we observe that two images associated with the mantle plume, one from the seismic data and another from the MT data, are very similar. This consistency is a good indication that these two models manifest the same or interacting large-scale compositional structure in the upper mantle under the Yellowstone National Park.

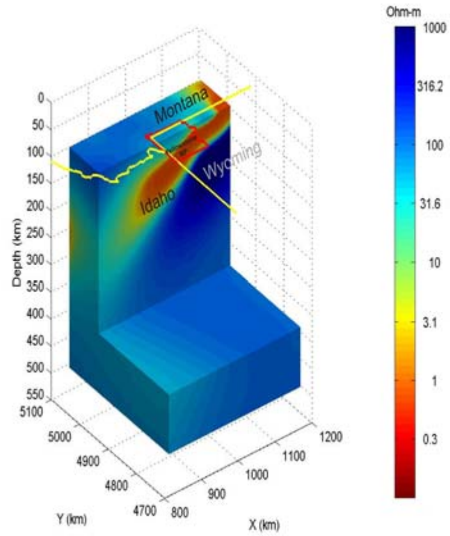

Figure 5. *3D resistivity model obtained by 3D inversion of MT data over Yellowstone Park. The model shows a plume-like structure of hot conductive rock originating in the mantle transition zone. The vertical section transects the Yellowstone National Park, and the horizontal sections are drawn at a depth of 500 km.*

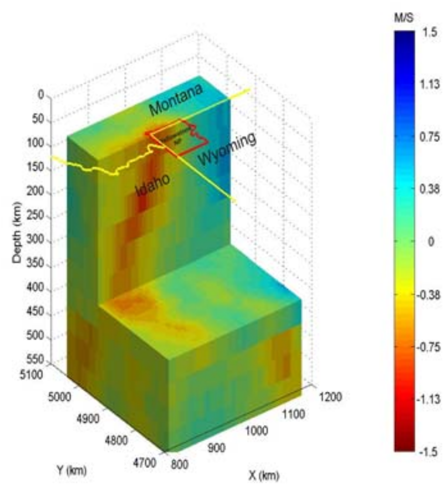

Figure 6. *3D velocity model obtained by 3D P-wave seismic tomographic imaging over Yellowstone Park. The model shows a rising column of partly molten rock originating in the mantle transition zone. The vertical section transects the Yellowstone National Park, and the horizontal sections are drawn at a depth of 500 km.*

Large-scale 3D MT inversion of EarthScope data

The observed differences in the 3D earth models should be expected considering the different physical nature of seismic and MT data, different survey configurations, and different depth resolutions of the two geophysical techniques. The P-wave velocity model from seismic tomography is indicative of the elastic properties of the rocks, while the resistivity model from MT inversion is indicative of the electrical properties of the same rocks. Because of the physical nature of the low-frequency diffusion EM field, it has much lower resolution than the seismic wavefield (Zhdanov, 2002, 2009). In fact, the depth resolution of the MT data below 300 km is very small because of the rapid attenuation of the electromagnetic fields with the depth. This fact explains an absence of visible anomalies below 300 km in the earth models. Nevertheless, the general character of the conductivity and velocity models shows remarkable similarity, which indicates the presence of the mantle plume associated with the hot material rising from the mantle toward the Yellowstone caldera.

Smith et al. (2009) have interpreted this conduit-shaped low-velocity body as a plume of 1% to 3.5% Vp and -5.5% Vs perturbation that corresponds to a 1 to 2% partial melt. This interpretation corresponds well to a model of mantle convection return flow, which reveals eastward upper-mantle flow beneath Yellowstone at relatively high rates of 5 cm/yr that deflects the ascending plume into its west-tilted geometry (Schutt et al., 2008). A geodynamic model of the Yellowstone plume constrained by Vp and Vs velocities and attenuation parameters suggests low excess temperatures of up to 120 K, corresponding to a maximum 2.5% melt (Waite et al., 2005, 2006; Smith et al., 2009). The partly melted hot material forming the plume should have a high electrical conductivity, and this is confirmed in the 3D earth model obtained from MT inversion. We specifically note that new studies of the Yellowstone plume include analyses of seismic wave attenuation for P- and S-waves (e.g., Adams and Humphreys, 2010). These studies have revealed relatively high attenuation of the mantle volume which is imaged as the Yellowstone plume, and this is interpreted to reflect a partially molten plume in which water is partitioned into the melt and surrounded by a cooler and wetter mantle. A notable attenuation decrease between 200 km and 250 km is considered by Adams and Humphreys (2010) as evidence that the plume is melting above this depth. This corresponds well to the area of high conductivity above 250 km in the 3D resistivity model shown in Figure 4.

Conclusions

We have applied our method of 3D MT inversion with a receiver footprint to invert continental-scale MT data acquired as a part of the EarthScope project. Our 3D resistivity model of the upper mantle under Yellowstone provides an independent confirmation of the presence of a plume of hot conductive material rising from the mantle towards the Yellowstone volcano, based on MT data. Importantly, the conductive structure independently correlates spatially with the P- and S- wave low-velocity structures in the upper mantle that are interpreted as the Yellowstone plume.

Acknowledgements

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Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2011 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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