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Key Points:
- Geoelectrical model of the East Central United States is determined by 3-D inversion of the long period magnetotelluric data
- Recovered conductivity anomalies indicate a possible hot spot track in the area, which correlates well with the *P* wave velocity model
- An efficient method of 3-D inversion of magnetotelluric data is presented

Supporting Information:
- Supporting Information S1
- Figure S1
- Figure S2
- Figure S3

Correspondence to:
A. V. Gribenko,
alex.gribenko@utah.edu

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3-D Inversion of the MT EarthScope Data, Collected Over the East Central United States

A. V. Gribenko[1,2] and M. S. Zhdanov[1,2]

[1]University of Utah, Salt Lake City, UT, USA, [2]TechnoImaging, LLC, Salt Lake City, UT, USA

Abstract The magnetotelluric (MT) data collected as a part of the EarthScope project provided a unique opportunity to study the conductivity structure of the deep interior of the North American continent. Besides the scientific value of the recovered subsurface models, the data also allowed inversion practitioners to test the robustness of their algorithms applied to regional long-period data. In this paper, we present the results of MT inversion of a subset of the second footprint of the MT data collection covering the East Central United States. Our inversion algorithm implements simultaneous inversion of the full MT impedance data both for the 3-D conductivity distribution and for the distortion matrix. The distortion matrix provides the means to account for the effect of the near-surface geoelectrical inhomogeneities on the MT data. The long-period data do not have the resolution for the small near-surface conductivity anomalies, which makes an application of the distortion matrix especially appropriate. The determined conductivity model of the region agrees well with the known geologic and tectonic features of the East Central United States. The conductivity anomalies recovered by our inversion indicate a possible presence of the hot spot track in the area.

Plain Language Summary The magnetotelluric (MT) data collected as a part of the EarthScope project provided a unique opportunity to study the conductivity structure of the deep interior of the North American continent. In this paper we consider the southern part of the second footprint covered by 246 MT stations. Chu et al. (2013) identified a linear seismic anomaly in the lower lithosphere, which was interpreted as a hot spot track. Hot spot tracks are thought to be the surface expressions of tectonic plates moving over upwelling mantle plumes. At present, most hotspot tracks are observed on oceanic or thin continental lithosphere. Both partial melting and the presence of graphite and sulfide can increase electrical conductivity of the lithosphere. Our inversion model indicates a presence of relatively conductive rocks in the general vicinity of the hotspot path, interpreted by Chu et al. (2013). The conductive anomalies coincide with the proposed hotspot track in its eastern part but appear shifted to the south in the west.

1. Introduction

The magnetotelluric (MT) component of the EarthScope USArray program is a powerful instrument for regional-scale imaging of deep geoelectrical structure of the North American crust and upper mantle. Since 2006, the EarthScope's USArray has deployed large number of MT stations to measure the long-period data in areas of special interest as proposed by the MT community (2006–2011 in the Pacific Northwest, 2011–2013 in the Mid-Continent Rift, and 2013–2017 in the southeastern USA). The observations in every MT site were conducted for approximately 3 weeks with a nominal 70 km grid spacing. The observed data were archived with Incorporated Research Institutions for Seismology (IRIS); they were processed into the MT transfer functions (http://www.usarray.org/researchers/obs/magnetotelluric). The data can be downloaded from IRIS webpage: http://ds.iris.edu/spud/emtf.

Many researchers contributed to the interpretation of the first footprint of the EarthScope MT data over the western United States (Bedrosian & Feucht, 2014; Cuma et al., 2017; Meqbel et al., 2014; Patro & Egbert, 2008; Zhdanov et al., 2010, 2011, 2012). Yang et al. (2015) presented the results of inversion of the data from the northwestern part of the second MT data footprint. In this paper we consider the southern part of the second footprint covered by 246 MT stations. Murphy and Egbert (2017) published recently the results of MT inversion in the area to the south of the area considered in our paper.

Before presenting the EarthScope inversion results, we briefly describe the main features of our inversion method. In order to take into account the near-surface inhomogeneities, we have inverted for 3-D conductivity distribution and for a distortion matrix simultaneously, as discussed in Gribenko and Zhdanov (2015) and Avdeeva et al. (2015). This allows us to take into account not only the conventional direct current static shift but also possible phase changes of the impedance tensor. We use the integral equation forward modeling method, which ensures an accurate solution of the forward problem and provides an effective algorithm for the Frechet derivative (sensitivity) matrix calculation without any additional forward modeling required. Our inversion algorithm also uses a concept of the variable sensitivity domain, which significantly reduces memory and computer power requirements (Cuma et al., 2017). A model study on a scale similar to the EarthScope data demonstrates the performance of our algorithm in the presence of small, near-surface conductivity anomalies.

Chu et al. (2013) identified a linear seismic anomaly in the lower lithosphere extending eastwards from Missouri to Virginia, cross-cutting the New Madrid rift system, and then bending northward. The anomaly was characterized by both reduced *P* wave velocity and high attenuation. Chu et al. (2013) interpreted the anomaly as a hot spot track, thought to be the surface expressions of tectonic plates moving over upwelling mantle plumes. At present, most hot spot tracks are observed on oceanic or thin continental lithosphere. For an old, thick continental lithosphere, such as the Eastern United States, the hot spot tracks are mainly inferred from the sporadic diamondiferous kimberlites sourced from the deep mantle (Torsvik et al., 2010). Besides causing reduced seismic velocity and increased attenuation, the residual heat from the plume can cause partial melting of the deep lithosphere. Graphite crystals are also present in the mantle xenoliths and kimberlites (Robinson, 1979).

There are competing explanations of the origin of the seismic anomaly identified by Chu et al. (2013). Mazza et al. (2014) examined the geochemical characteristic of the volcanics that were found above the West Virginia/Virginia (WV/VA) anomaly (part of the Chu et al. hot spot track) and concluded that a delamination event, rather than hot spot activity, best explained those rocks. Schmandt and Lin (2014) produced a continental U.S. body wave image indicating that the WV/VA anomaly was likely not due to the hot spot activity. The results of our MT inversion indicate, however, a presence of relatively conductive rocks in the general vicinity of the hot spot path, interpreted by Chu et al. (2013). Both partial melting and the presence of graphite and sulfide can increase electrical conductivity of the lithosphere (Selway, 2014; Yardley & Valley, 1997). The conductive anomalies coincide with the proposed hot spot track in its eastern part but appear shifted to the south in the west.

2. Inversion of MT Data for Conductivity and Distortion Matrix

Magnetotelluric (MT) method has been described in a number of publications (e.g., Berdichevsky & Dmitriev, 2002; Zhdanov & Keller, 1994). It is based on measuring the horizontal components of the natural electromagnetic field of the Earth and computing the transfer functions between different components expressed in the form of the MT impedance tensor, $\boldsymbol{Z}^{\mathrm{obs}}$. The observed MT responses can be inverted for subsurface electrical conductivity distribution.

The distortions of regional MT responses by local near-surface geoelectrical inhomogeneities cause major difficulties in interpretation of the MT data. The distortion effect can be formally taken into account by representing the observed MT impedance tensor as a product of the undisturbed impedance tensor and a distortion matrix (Groom & Bailey, 1989):

$$\boldsymbol{Z}^{\mathrm{obs}} = \left[c_{ij}\right]\left[\boldsymbol{Z}_{\alpha\beta}^{\mathrm{reg}}\right], \tag{1}$$

where $[c_{ij}]$ is the distortion matrix and $\left[\boldsymbol{Z}_{\alpha\beta}^{\mathrm{reg}}\right]$ is the matrix of the regional undisturbed impedance tensor, which depends on the conductivity distribution within the deep geoelectrical structures. Our interpretation method is based on simultaneous inversion of the observed MT impedance tensor for the distortion matrix and deep conductivity distribution using Tikhonov regularization (Tikhonov & Arsenin, 1977; Zhdanov, 2009, 2002, 2015). The details of this inversion approach can be found in the supporting information, section S1.

3. Inversion of the MT Data Collected by the Second Footprint of the EarthScope MT Array

Figure 1 shows the locations of the EarthScope MT stations. The magenta box approximately outlines 246 MT stations used in this inversion. We applied the joint conductivity and distortion matrix inversion to the MT

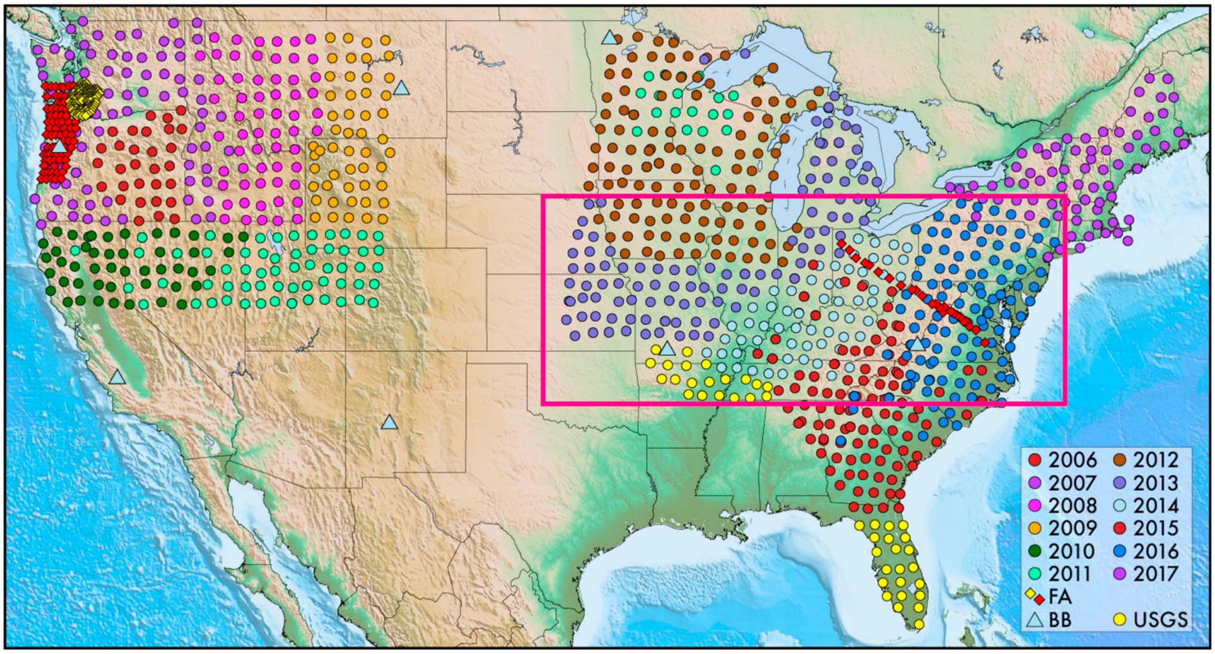

Figure 1. A map of the locations of the EarthScope MT stations. The magenta box approximately outlines 246 MT stations used in the inversion presented in this letter.

impedance data collected by the second footprint of the EarthScope MT array. The inversion domain was extended at approximately 1,500 km in the north-south direction and at 2,670 km in the east-west direction. The horizontal cell size was selected at 15 × 15 km^2. The vertical discretization consisted of 36 layers with the thickness increasing logarithmically from 1 to 50 km. We selected the depth of inversion domain equal to 465 km based on our practical observation that the sensitivity of the EMScope MT data, generally, decreases significantly at a depth over 450 km. This effect was evaluated by numerical modeling in the recently published paper by Cuma et al. (2017). A half-space with the resistivity of the bottom layer was assumed below this depth. The inversion domain was discretized in 640,800 cells.

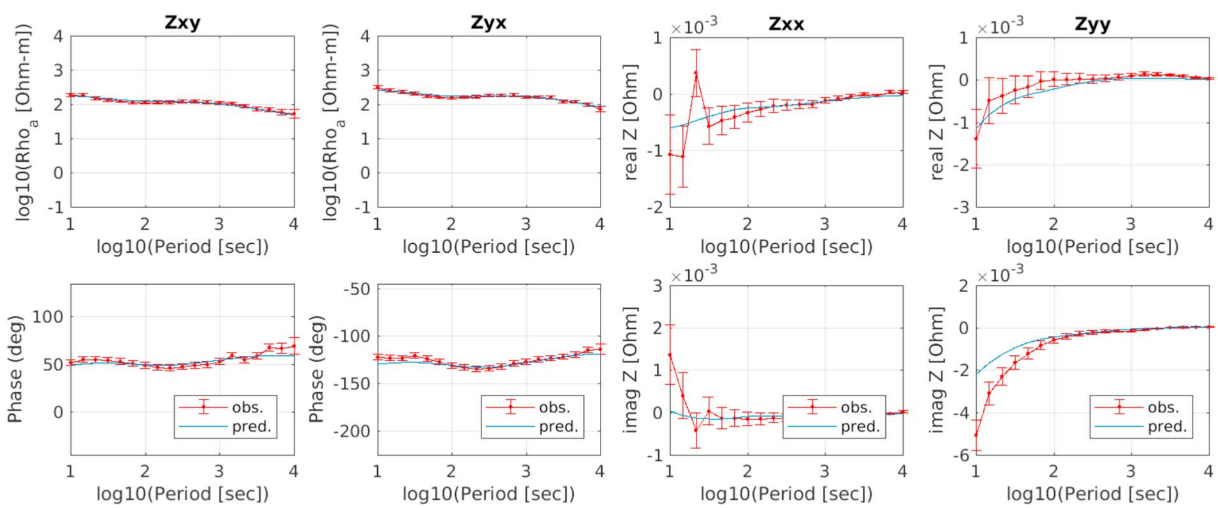

Figure 2. The plots of the apparent resistivities and phases observed (red lines) and predicted (blue lines) by 3-D inversion for one of the MT stations shown in Figure 4 below by magenta cross. The two left columns show the (top row) observed and predicted apparent resistivities and (bottom row) phases of the principal impedances Z_{xy} and Z_{yx}. The two columns on the right present the (top row) observed and predicted real and (bottom row) imaginary parts of the diagonal impedances Z_{xx} and Z_{yy}.

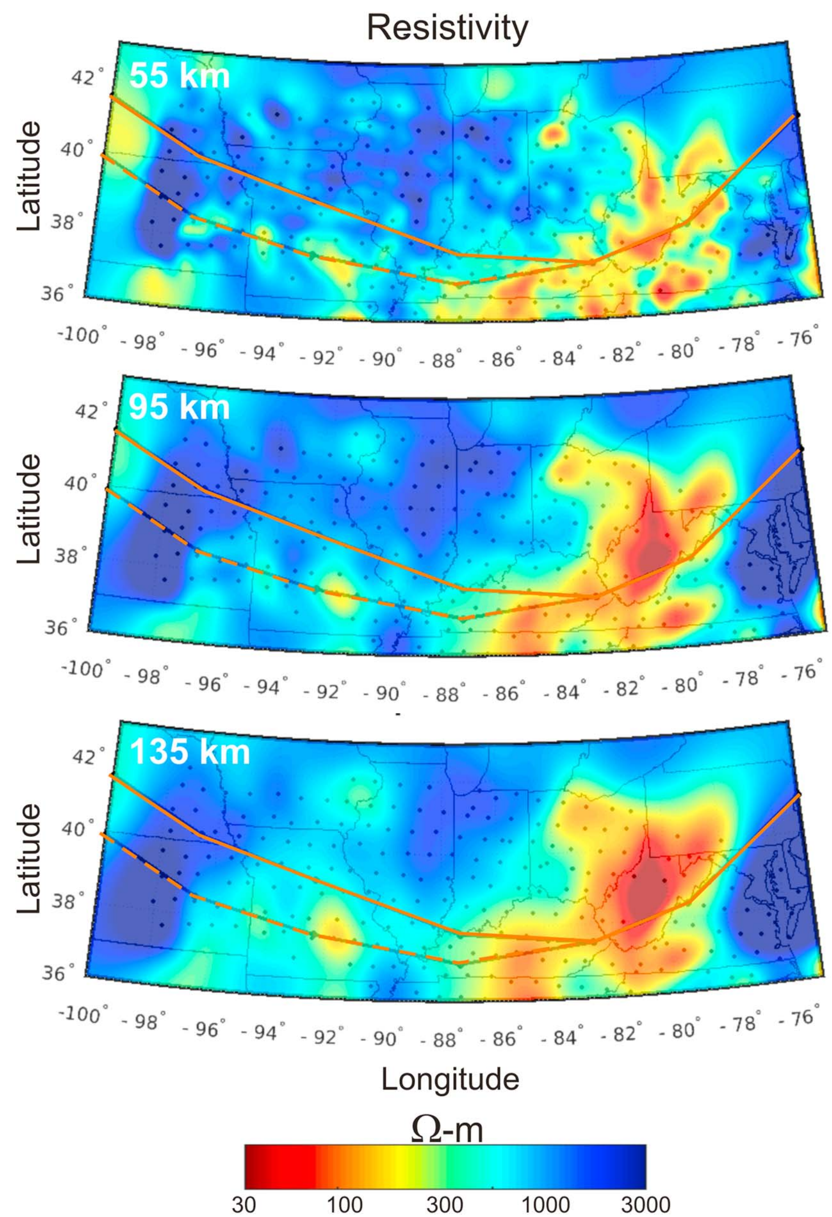

Figure 3. Maps of resistivity distributions produced by the inversion at (top) 55 km, (middle) 95 km, and (bottom) 135 km depths. The hot spot track, proposed by Chu et al. (2013), is shown by the solid red lines. The dashed red lines represent a hot spot track suggested by the resistivity distribution.

We used a horizontally layered model as a starting model for 3-D inversion. This 1-D model was produced by inverting the MT sounding curve obtained by averaging the data over all stations. A single computing node with 20 processor threads was used for the computation. CPU time for the inversion was approximately 84 h. The 3-D inversion run for 2,320 iterations and reached nRMS = 2.87. The error floor of 5% of the principal impedance values was assumed in calculating nRMS, which was computed by the following formulas:

$$\boldsymbol{r} = \boldsymbol{W_d}\left(\boldsymbol{d_{pred}} - \boldsymbol{d_{obs}}\right), \quad \boldsymbol{nRMS} = \sqrt{\frac{\boldsymbol{r^T r}}{\boldsymbol{N_d}}}, \tag{2}$$

where $\boldsymbol{d_{pred}}$ is the vector of the predicted data, $\boldsymbol{d_{obs}}$ is the vector of the observed data, $\boldsymbol{W_d}$ is the data weighting matrix with the weights computed as an inverse of the noise level (variance), $\boldsymbol{r}$ is the vector of weighted residuals, $\boldsymbol{N_d}$ is the total number of data entries, and superscript $\boldsymbol{T}$ indicates a transposed vector. An elevated

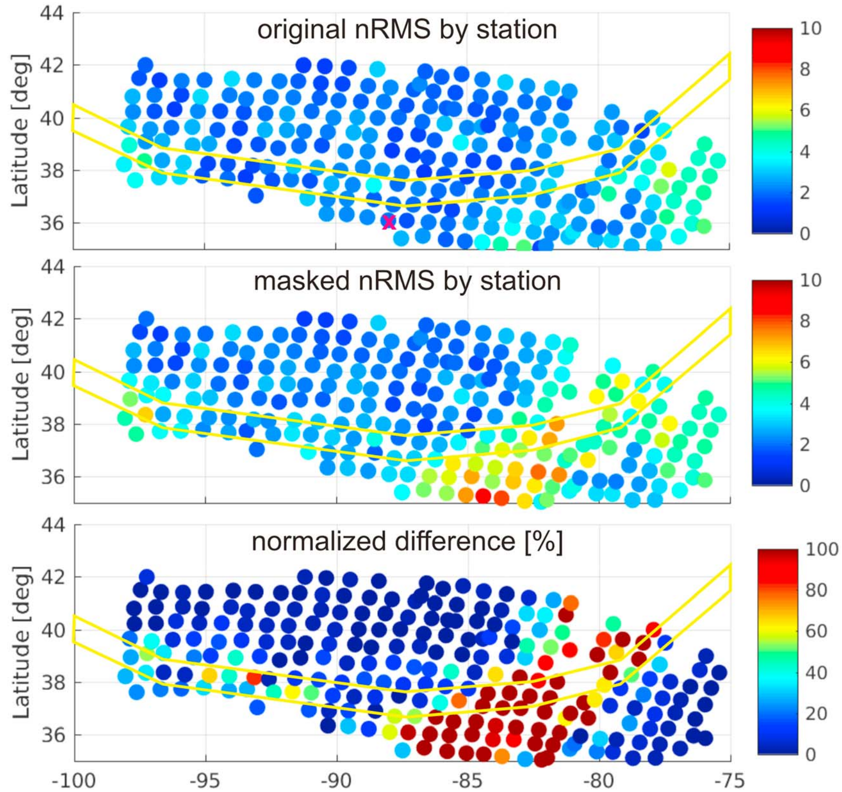

Figure 4. nRMS distributions by station. (top) nRMS values for the inverse model presented in the paper. (middle) nRMS distribution for the masked model. (bottom) Normalized percent difference of the nRMS values for the two models. The station corresponding to the sounding curves in Figure 2 is marked by magenta cross. The bold yellow lines are the borders of a strip 100 km wide, covering the location of the proposed hot-spot track, shown by the red dashed lines in Figures 3 and 5.

value of nRMS is probably related to the relatively large level of noise in the observed data and to the effect of the ocean, which we will discuss below.

Figure 2 shows the apparent resistivities and phases observed and predicted by 3-D inversion for one of the MT stations, as an example. The location of this station is shown in Figure 4 below by magenta cross. Figure 3 presents the horizontal sections of the resistivity distribution obtained by 3-D MT inversion at 55 km (top), 95 km (middle), and 135 km (bottom) depths. In this figure, one can see significant conductive anomalies in the southern and eastern regions of the inversion domain.

4. Hotspot Track Inferred From 3-D Resistivity Distribution

Chu et al. (2013) used seismic waveforms initiated by the 2011 M_w 5.6 Virginia earthquake, recorded by the seismic observation network USArray, to analyze the structure of the continental lithosphere in the eastern United States. They identified an unexpected linear seismic anomaly in the lower lithosphere that had both a reduced *P* wave velocity and high attenuation, and which was interpreted as a hot spot track. The anomaly extends eastward, from Missouri to Virginia, cross-cutting the New Madrid rift system, and then bends northward. It has no clear relationship with the surface geology but passes near a 100-million-old kimberlite in Riley, Kansas, and crosses a 75-million-year-old kimberlite in Elliot, Kentucky. Chu et al. (2013) suggested that the hot spot track could be responsible for the late Mesozoic reactivation of the New Madrid rift system and seismicity of the eastern United States. There have been alternative interpretations of the anomaly associated with the eastern part of the alleged hot spot track (Chu et al., 2014; Evans et al., 2016; Mazza et al., 2014; Schmandt & Lin, 2014). Mazza et al. (2014) studied the geochemistry of the volcanics that were found above the hot spot track in West Virginia and Virginia (WV/VA). They concluded that the anomaly corresponded to delamination event, rather than hot spot activity.

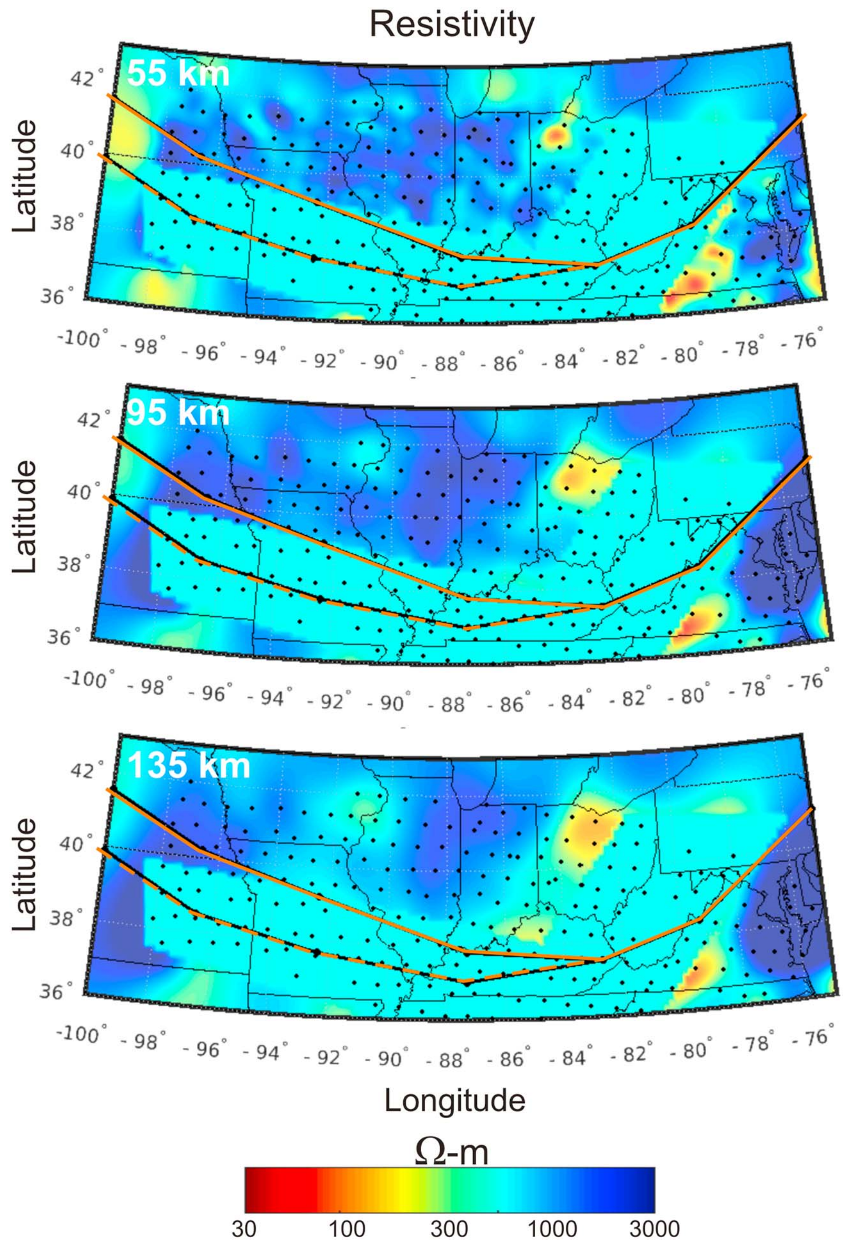

Figure 5. Maps of resistivity distributions at (top) 55 km, (middle) 95 km, and (bottom) 135 km depths. Low resistivities along the alleged hot-spot track had been replaced by 500 Ω m cells. The hot spot track, proposed by Chu et al. (2013), is shown by the solid red lines. The dashed red lines represent a hot spot track suggested by the resistivity distribution.

In order to compare the results of MT inversion with the velocity model, produced by Chu et al. (2013), we present in Figure 3 both the horizontal sections of the resistivity distribution obtained by our MT inversion and the hot spot track proposed by Chu et al. (2013) (shown by the solid red line). The dashed red line connects several conductive anomalies appearing to the south of the track based on the *P* wave velocity anomaly. It is possible that conductive anomalies are associated with the residual heat and partially melted rock caused by the hot spot. The graphite and/or sulfide particles, emplaced by the kimberlites and rifting along the path of the hot spot, may also be the reasons for the decreased resistivity. Figure S3 in supporting information provides vertical sections through the WV/VA part of the anomaly, which was interpreted by Mazza et al. (2014) to be a delamination event.

5. Analysis of the Sensitivity of the MT Data to the Conductive Anomalies Recovered by the Inversion

In this section, we evaluate the inversion results more carefully by first analyzing the spatial behavior of the nRMS for this survey. Figure 4 (top) presents a distribution of the data fit (nRMS) over the survey area in different MT stations. The observed data for majority of the stations were predicted to an acceptable value of nRMS < 2. At the same time, several stations in the easternmost part of the domain were characterized by the elevated values of the misfit caused by the proximity of the ocean, which was not included in the starting model. By excluding the MT stations located east of $-78°$, we were able to reduce the nRMS to 2.2, which we believe is acceptable for this large-scale inversion. What is important, however, is that the value of nRMS is still below 2 over the suggested hot spot conductor, which confirms the presence of the conductor in this region.

In order to investigate this question even deeper, we have conducted a sensitivity test, which demonstrates that the MT data are indeed sensitive to the conductive anomalies discovered along the proposed hot spot track. To test the sensitivity of the data, we modified the inverse model to mask the conductive anomalies in the southern and eastern regions of our inversion domain as shown in Figure 5. The depth extent of the masked area was selected from 30 to 200 km. The resistivity of the masked area was set at 500 Ω m. A similar resistivity value appears outside of the conductive anomaly within this depth range.

The forward response and nRMS values for the masked model shown in Figure 5 had been also computed. They appear in the middle panel of Figure 4. The bold yellow lines in all three panels outline the borders of a strip approximately 100 km wide, covering the location of the proposed hot spot track. There is a significant increase in the nRMS values within this strip along the masked portion of the model, ranging from 30 to over 100%. This indicates that the MT data have strong sensitivity to the conductive features recovered by our inversion along the proposed hot-spot track.

6. Conclusions

We have analyzed the EarthScope MT data by a method of simultaneous inversion of magnetotelluric impedance tensor for the distortion matrix and deep conductivity distribution. Our method is based on the contraction integral equation formulation of the forward modeling problem for the EM fields and Tikhonov regularization.

We inverted MT data from 246 MT stations located in the southern part of the second EarthScope MT footprint. Bedrosian (2016) studied the conductivity distribution around the Midcontinent Rift, which is located to the north from the area considered in this study. Murphy and Egbert (2017) presented results of MT inversion in the area to the south of this area; however, several stations from the southeastern part of our domain appear in the both studies. The conductivity distribution obtained by our inversion is in a general agreement with the one found by Murphy and Egbert (2017) for the overlapping area. The northern tip of the Piedmont resistor may be present in our inversion result as well. We present conductivity sections from this region in the supporting information for a comparison.

Based on the results of our 3-D inversion, we identified several conductive anomalies in the lower part of the lithosphere. These anomalies appear in the vicinity of the hot spot track proposed by Chu et al. (2013) based on *P* wave velocity and attenuation anomalies. The conductive anomalies coincide with the proposed hot spot track in its eastern part but appear shifted to the south in the west. The possible reasons for the increased conductivity of the lithosphere are partial melting and the presence of graphite and sulfide particles emplaced by kimberlites and rifting along the hot spot track (Selway, 2014; Yardley & Valley, 1997).

We consider that these results are preliminary and require a more detailed geological analysis. Nevertheless, the geoelectrical model produced by inversion of the EarthScope MT data should be taken into account in the final determination of the presence of the hot spot activity in the survey area.

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