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Three-dimensional electrical resistivity of the north-central USA from EarthScope long period magnetotelluric data

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ABSTRACT

We present initial results from three-dimensional inversion of long period EarthScope magnetotelluric (MT) transportable array data from 232 sites covering the north-central US. The study area covers the 1.1 Ga Mid-Continent Rift (MCR) system, which cuts across a series of Archean and Paleoproterozoic lithospheric blocks. The western arm of the MCR is clearly evident in shallow depth sections, with a narrow resistive core, flanked by elongate conductive basins. Other prominent upper-crustal features mapped include the moderately conductive Michigan and Illinois Basins, and extremely high conductivities in foreland basin rocks at the southern margin of the Superior craton. The most prominent conductive anomalies, in an otherwise relatively resistive mid-lower crust, are two elongate east–west oriented structures, which are closely aligned with previously inferred continental sutures. The first underlies the southern margin of the Superior craton just north of the Niagara Fault (NF), and can be associated with the ∼1.85 Ga Penokean Orogeny. A second, further south beneath Iowa and western Wisconsin, lies just south of the Spirit Lake tectonic zone (SLtz), and can be identified with Yavapai accretion at ∼1.75 Ga. Both of these conductive sutures are cleanly cut by the MCR, which is otherwise not clearly evident in the deeper parts of the resistivity model. The break in the anomalies is narrow, comparable to the surface expression of the MCR, indicating that rifting impacts on the entire crustal section were highly localized. Both suture-related anomalies are imaged as extending into, and perhaps through, the lithosphere as dipping diffuse zones of reduced mantle resistivity. Sense of dip of these structures (southward for the NF anomaly, northward for SLtz) agrees with previously inferred models for subduction and accretion, suggesting that a conductive phase (most likely carbon) has been thrust deep into the lower crust and uppermost mantle, providing a marker of the three-dimensional boundary between lithospheric blocks. Resistivities drop below ∼100 Ω m below ∼200 km depth, in rough agreement with the seismically determined lithosphere–asthenosphere boundary (LAB). There are modest lateral variations in this deep low-resistivity layer, but the reliability and significance of these are not yet clear.

1. Introduction

The magnetotelluric (MT) component of the EarthScope USArray program is a powerful tool for regional-scale imaging of deep 3D electrical resistivity variations in the North American crust and upper mantle (e.g., Meqbel et al., 2014). Here we present results from the second EarthScope long period MT data footprint, consisting of 232 sites covering the north-central USA, collected during 2011–2013 with the seismic transportable array nominal site spacing of 70 km. In contrast to the tectonically active Northwestern United States covered by the first footprint (Patro and Egbert, 2008; Zhdanov et al., 2011; Meqbel et al., 2014; Bedrosian and Feucht, 2014), this area has been stable over at least the entire Phanerozoic. The most recent significant geotectonic event, at 1.1 Ga, was the development of the mid-continent rift (MCR), by far the most notable geophysical anomaly in the region, especially in gravity and magnetics (e.g., Hildebrand, 1985; Chandler et al., 1989). The MCR cuts across geological provinces of much greater age (e.g., Hoffman, 1989), from the Archean Superior Province in the north to the Paleoproterozoic Yavapai and Mazatzal Provinces in the south (Fig. 1).

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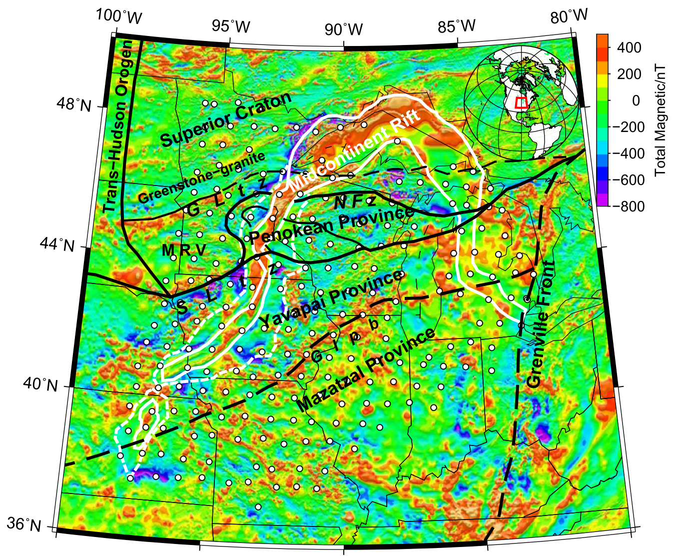

Fig. 1. Map of study area, showing magnetic anomaly map (USGS website: http://mrdata.usgs.gov/magnetic/); MT site locations (white circle), geologic terrane map of Precambrian basement rocks (after Holm et al., 2007 and Renee Rohs and Van Schmus, 2007); MCR boundaries (after Renee Rohs and Van Schmus, 2007); GIpb: Green Island plutonic belt; GLtz: Great Lakes tectonic zone; MRV: Minnesota River Valley subprovince; NFz: Niagara Fault zone; SLtz: Spirit Lake tectonic zone.

Modern interpretations of the study area, based primarily on precise geochronology and refined compilations of potential field data, are summarized in Holm et al. (2007), with further details and graphical summaries of accretionary events provided by Van Schmus et al. (2007) (Fig. 6) and Schulz and Cannon (2007) (Fig. 6). In this area, the Superior Province is divided into the Greenstone–Granite (2.6–3.6 Ga), and the Minnesota River Valley (3.4–3.6 Ga) subprovinces, respectively south and north of the Great Lakes tectonic zone (GLtz; Fig. 1). South of the Superior Province and east of Minnesota River Valley lies the Penokean Province, accreted between 1.8 and 1.9 Ga. On the surface, the boundary between the Superior and Penokean Provinces is defined by the Niagara Fault zone (NF). To the north, extensive foreland basin rocks lap onto the craton margin domain, an assemblage consisting of sedimentary and volcanic rocks deposited during the interval 2.3–1.77 Ga (Holm et al., 2007). The Penokean Province, and the Minnesota River Valley to the west, are bounded on the south by the Spirit Lake tectonic zone (SLtz; Fig. 1), marking the transition to the Yavapai Province, accreted at 1.7–1.8 Ga. First identified in the more exposed southwest USA, the juvenile arc rocks of the Yavapai Province are now generally thought to extend into southern Ontario (Van Schmus et al., 2007). Assembly of the continent in this area was completed with accretion of the Mazatzal province at 1.6–1.7 Ga.

The final important regional tectonic event was creation of the MCR at 1.1 Ga. In the standard interpretation (e.g., Keller et al., 1983), the MCR represents a failed continental rift. Geochemistry of exposed rift basalts, mostly near Lake Superior, suggests that a mantle plume may have initiated rifting (Nicholson et al., 1997). The rifting was terminated within ∼30–50 m.y., possibly due to a change in the compressional stress regime associated with initiation of the Grenville Orogeny (e.g., Cannon and Hinze, 1992), as indicated by thrust faulting on the flanks (Cannon, 1994), and thickened crust underlying the rift (Shen et al., 2013). Stein et al. (2014) offered an alternative interpretation of MCR evolution, suggesting that the rifting was initiated as part of successful larger-scale continental rifting of Amazonia from Laurentia, which became inactive in the interior once seafloor spreading was established.

Although the MCR was a major target of the second EarthScope MT footprint, we will show that the most striking conductivity anomalies in this region, which generally has moderately resistive lithosphere, are associated with two Paleoproterozoic suture zones resulting from Penokean and Yavapai subduction and accretion. At least the near surface expressions of some of these conductive features have been glimpsed by previous EM studies (Sternberg and Clay, 1977; Boerner et al., 1996), but here we provide a more comprehensive 3D regional view, extending to asthenospheric depths. Except in the upper crust, resistivity variations associated with the MCR are more subtle. Indeed, the deep structure of the MCR is most clearly expressed in our resistivity images as gaps cut through the evidently older lower crustal conductive structures.

2. Magnetotelluric data and inversion

The EarthScope MT data were acquired using long period instruments based on fluxgate magnetometers, and were processed using a standard robust remote reference algorithm (Egbert and Booker, 1986; Egbert, 1997) to produce impedances (**Z**) and vertical transfer functions (VTFs). The data quality is very good for most stations, although a few sites near densely populated area were contaminated by cultural noise, and were omitted for the inversions shown here.

We employed the Modular system for Electromagnetic Inversion (ModEM, Egbert and Kelbert, 2012; Kelbert et al., 2014) for 3D modeling and inversion. The 3D resistivity model presented in this study was obtained by jointly inverting the full impedance and VTFs from 222 stations (Fig. 1) at 28 periods, ranging from 11 s to 18 725 s for **Z**. For VTFs, only periods shorter than 7281 s were used to avoid biases due to finite source spatial scale, a more serious problem for VTFs than for impedances (e.g., Dmitriev and Berdichevsky, 1979). The data are presented and discussed further in the Supplementary material.

We assigned error floors of 5% of $|Z_{xy} \cdot Z_{yx}|^{1/2}$ for all four **Z** components and a constant value of 0.03 for VTFs, comparable to levels used in previous regional scale 3D inversions (e.g. Meqbel et al., 2014; Bedrosian and Feucht, 2014). The study area was discretized with a 20 km grid in the core, padded with 7 cells on all edges, with widths increasing by a factor of 1.2 outward to the boundary. Vertically, 54 layers were used, starting from 50 meters and increasing logarithmically with a factor of 1.12. This discretization resulted in a $98 \times 83 \times 61$ grid, in the x, y and z directions, including 7 air layers. Note that the Great Lakes are relatively shallow (roughly 100 m on average) with resistivity close to 100 Ω m (Doherty, 1963), so we have not deemed it necessary to include lake bathymetry in prior models.

Eighteen runs have been conducted varying inversion parameters, (e.g., length scales of model smoothing), subsets of data fit (impedances only, impedance and VTFs jointly, subsets of periods), and prior models (100 Ω m half-space, 200 Ω m half-space, 1D layered model). As in Meqbel et al. (2014), we rely on a fine enough parameterization of the uppermost layers to accommodate near surface distortion. To further reduce possible near surface static shift effects, for some inversion runs we tested a strategy of reducing the smoothing parameters for layers shallower than 2 km. This produced rougher shallow structure, and concentrated high and low resistivities in the near surface layers, resulting in slightly smoother and simpler deep structure. We used this strategy for the preferred inverse solution shown below. For this solution, we first fit **Z** only, adopting a 100 Ω m half-space prior model. Convergence, to a normalized root mean square misfit (nRMS) of 1.83, required 130 iterations of the nonlinear conjugate gradient (NLCG) scheme used in ModEM. We then restarted the inversion to fit **Z** and VTFs jointly, using an additional 112 iterations to fit the full dataset to a nRMS of 1.84. Adding the VTF data resulted in some-