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Making it and breaking it in the Midwest: Continental assembly and rifting from modeling of EarthScope magnetotelluric data

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ABSTRACT

A three-dimensional lithospheric-scale resistivity model of the North American mid-continent has been estimated based upon EarthScope magnetotelluric data. Details of the resistivity model are discussed in relation to lithospheric sutures, defined primarily from aeromagnetic and geochronologic data, which record the southward growth of the Laurentian margin in the Proterozoic. The resistivity signature of the 1.1 Ga Mid-continent Rift System is examined in detail, in particular as relates to rift geometry, extent, and segmentation. An unrecognized expanse of (concealed) Proterozoic deltaic deposits in Kansas is identified and speculated to result from axial drainage along the southwest rift arm akin to the Rio Grande delta which drains multiple rift basins. A prominent conductor traces out Cambrian rifting in Arkansas, Missouri, Tennessee, and Kentucky; this linear conductor has not been imaged before and suggests that the Cambrian rift system may have been more extensive than previously thought. The highest conductivity within the mid-continent is imaged in Minnesota, Michigan, and Wisconsin where it is coincident with Paleoproterozoic metasedimentary rocks. The high conductivity is attributed to metallic sulfides, and in some cases, graphite. The former is a potential source of sulfur for multiple mineral deposits types, occurrences of which are found throughout the region. Finally, the imprint left within the mantle following the 1.1 Ga rifting event is examined. Variations in lithospheric mantle conductivity are observed and are interpreted to reflect variations in water content (depleted versus metasomatized mantle) imprinted upon the mantle by the Keweenawan mantle plume.

1. Introduction

The North American mid-continent presents a window into craton growth and stabilization as well as the 1.1 Ga rifting event that nearly tore Laurentia apart. Unique to this region is the preservation of this tectonic collage, largely unmodified by subsequent tectonic events, which permits examination of how such events are preserved in the continental lithosphere.

Phanerozoic sedimentary rocks cover most of the North American mid-continent, limiting our ability to directly sample the underlying Precambrian collage. As such, current understanding of the structural evolution of the region is skewed heavily toward the northern United States and Canada, where outcrops are most abundant. Further south, sparse borehole data provide isolated windows into the petrology, geochronology, and isotopic signature of the Precambrian basement (e.g. Anderson, 1983; Bickford et al., 2015; Van Schmus et al., 2007). Geophysics plays a critical role in these areas, and potential-field data have revealed the basic structural evolution of the region (NICE working group, 2007). Recent seismic studies have examined the mid-continent at regional scales (e.g. Frederiksen et al., 2013a; Shen et al., 2013) while detailed seismic reflection studies greatly advanced the understanding of particular structures, such as the Mid-continent Rift System (MRS; Cannon et al., 1989; Woelk and Hinze, 1991; Zhu and Brown, 1986).

Electrical resistivity is a physical property that until recently has been applied only locally within the mid-continent, typically along profiles of less than 100 km in length. EarthScope magnetotelluric (MT) data present the first opportunity to examine resistivity in three-dimensions and at spatial scales necessary to investigate terrane-scale structure. I present here a three-dimensional (3D) lithospheric-scale resistivity model derived from EarthScope MT data collected from 2010 to 2014. I discuss details of the resistivity model in relation to lithospheric sutures that record the southward growth of the Laurentian margin in the Proterozoic. I examine in detail the resistivity signature of the 1.1 Ga MRS as relates to rift geometry, extent and segmentation. The model also reveals the distribution of highly conductive Paleoproterozoic metasedimentary rocks in Minnesota (MN), Wisconsin (WI), and Michigan (MI), and I discuss the origin of

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the high conductivity. Finally, I consider what, if any, imprint has been left within the mantle lithosphere in response to the 1.1 Ga rifting event.

In what follows I use the terms resistivity and conductivity, mathematical inverses of one another, interchangeably to describe the electrical properties of the subsurface. I also use both frequency and period, also inverses of one another, to describe the bandwidth of MT data in relation to depth of investigation. Finally, for compactness in describing geographic regions, I refer to states by their postal abbreviation, also shown in Fig. 1.

2. Geologic and tectonic framework

The North American mid-continent region was a locus of continental grown for over 1 billion years starting in the late Archean. The 1200+ km long Great Lakes tectonic zone (GLTZ, Fig. 1) is a paleosuture separating greenstone-granite terranes of the southern Superior craton (2.65 Ga) from early to late Archean gneiss (3.5–2.6 Ga) of the Minnesota river valley terrane (Sims, 1980). Sims et al. (1993) interpret the GLTZ to be the remnant of southward subduction and ultimate dextral transpression during continental collision at about 2.69 Ga.

The Superior craton began to undergo extension at 2.45 Ga (Heaman, 1997) and again from 2.21 to 2.1 Ga with emplacement of sills and dike swarms in Ontario and northern MN (Buchan et al., 1989; Southwick and Day, 1983). Near the southern edge of the craton, sedimentary rocks (Chocolay and Mille Lacs Groups) were deposited unconformably on the craton during the latter extensional episode. A subsequent extensional episode, underway by 1.91 Ga (Ojakangas et al., 2001), ended with crustal separation and creation of new ocean floor. Deposition during this time (Menominee and North Range Groups) began over a broad shelf along the Superior passive margin and ended within a series of backarc basins (Animikie and Baraga Groups) as south-directed subduction beneath arc rocks of the Wisconsin magmatic terranes (WMT) closed the short-lived ocean (Schulz and Cannon, 2007). These sedimentary rocks host economically important banded iron formations in MI, WI, MN, and Ontario. During the Penokean orogeny (~1.85 Ga), calc-alkaline volcanic and intrusive rocks of the WMT accreted to the Superior margin along the Niagara fault zone.

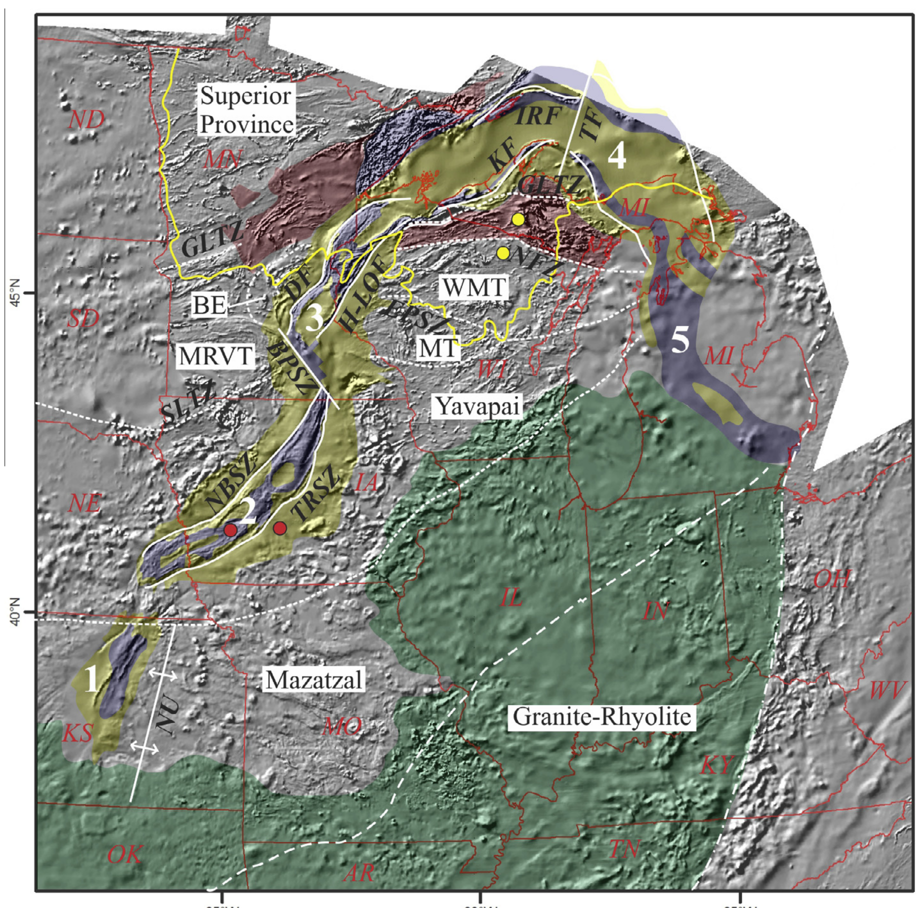

Fig. 1. Precambrian geology of the mid-continent region. Underlying hillshade is the total magnetic field anomaly. Yellow and blue shaded regions denote the known extent of Precambrian clastic and igneous rocks, respectively, associated with the 1.1 Ga Mid-continent Rift System (MRS). The MRS system can be separated into the Kansas rift segment (1), the Iowa horst (2), the St. Croix horst (3), the Superior graben (4), and the Michigan rift arm (5). Red shaded region denotes the recognized extent of 1.85 Ga Penokean deformation. Regions south of the yellow line are concealed beneath Phanerozoic cover. Green shaded region denotes the extent of 1.5–1.34 Ga anorogenic magmatism that defines the granite-rhyolite province (Bickford et al., 2015). Interpreted terrane boundaries (dotted white lines) are modified after the NICE working group (2007) and Whitmeyer and Karlstrom (2007). Dashed white line is the isotopic Nd line from (Bickford et al., 2015) and dash-dot line denotes the Grenville deformation front. Abbreviated terranes or sub-provinces include the Minnesota River Valley terrane (MRVT), the Becker embayment (BE), the Wisconsin magmatic terranes (WMT) and the Marshfield terrane (MT). Named terrane boundaries include the Great Lakes tectonic zone (GLTZ), the Spirit Lake tectonic zone (SLTZ), the Niagara fault zone (NFZ), and the Eau Pleine shear zone (EPSZ). Faults associated with the MRS include the Northern boundary structural zone (NBSZ), the Thurman Redfield structural zone (TRSZ), the Belle Plaine shear zone (BPSZ), the Douglas fault (DF), the Hastings-Lake Owen fault (H-LOF), the Keweenaw fault (KF), the Thiel fault (TF) and the Isle Royale fault (IRF). Nemaha uplift (NU). Red and yellow circles indicate magnetotelluric stations shown in Fig. 3a and b, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)