Tectonophysics 683 (2016) 367–381

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Anisotropic zonation in the lithosphere of Central North America: Influence of a strong cratonic lithosphere on the Mid-Continent Rift

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ARTICLE INFO

Article history:
Received 18 August 2015
Received in revised form 31 May 2016
Accepted 23 June 2016
Available online 29 June 2016

Keywords:
Mid-Continent Rift
Superior Province
Shear-wave splitting
Lithosphere
Anisotropy
Nipigon Embayment

ABSTRACT

We present shear-wave splitting analyses of SKS and SKKS waves recorded at sixteen Superior Province Rifting Earthscope Experiment (SPREE) seismic stations on the north shore of Lake Superior, as well as fifteen selected Earthscope Transportable Array instruments south of the lake. These instruments bracket the Mid-Continent Rift (MCR) and sample the Superior, Penokean, Yavapai and Mazatzal tectonic provinces. The data set can be explained by a single layer of anisotropic fabric, which we interpret to be dominated by a lithospheric contribution. The fast S polarization directions are consistently ENE-WSW, but the split time varies greatly across the study area, showing strong anisotropy (up to 1.48 s) in the western Superior, moderate anisotropy in the eastern Superior, and moderate to low anisotropy in the terranes south of Lake Superior. We locate two localized zones of very low split time (<0.6 s) adjacent to the MCR: one in the Nipigon Embayment, an MCR-related magmatic feature immediately north of Lake Superior, and the other adjacent to the eastern end of the lake, at the southern end of the Kapuskasing Structural Zone (KSZ). Both low-splitting zones are adjacent to sharp bends in the MCR axis. We interpret these two zones, along with a low-velocity linear feature imaged by a previous tomographic study beneath Minnesota and the Dakotas, as failed lithospheric branches of the MCR. Given that all three of these branches failed to propagate into the Superior Province lithosphere, we propose that the sharp bend of the MCR through Lake Superior is a consequence of the high mechanical strength of the Superior lithosphere ca. 1.1 Ga.

1. Introduction

Rifting a continent necessarily involves both the crust and the entire lithosphere. The mechanical strength of the continental lithosphere plays an important role in this process (Gueydan et al., 2008; Huismans and Beaumont, 2011), as the presence or absence of a strong lithosphere is a major control on the geometry and deformation mechanisms of the evolving rift. In addition, the mechanical fabric of the lithosphere may influence the directionality of the rifting process (Tommasi and Vauchez, 2001). Rifting processes are, to some extent, recorded in the lithospheric fabric beneath active (Bastow et al., 2010) as well as long-stable (Vauchez et al., 2000) rift zones, though strain localization in active rifts implies that broad anisotropic features will primarily record the early stages of rift development.

The Mesoproterozoic Mid-Continent Rift (MCR), in central North America, abuts on the Archean Superior Province (SP), the largest Archean craton in existence. The MCR cross-cuts the Proterozoic Penokean, Yavapai and Mazatzal orogens with both its eastern and western arms (Fig. 1), but avoids penetrating deep into the SP, instead bending sharply through Lake Superior. The MCR was recently instrumented with broadband seismographs as part of the Superior Province Rifting Earthscope Experiment (SPREE; Stein et al., 2011; Wolin et al., 2015), yielding the first detailed seismic constraints on the lithosphere of the MCR/Superior contact. In this study, we present the first observations of upper-mantle anisotropy made using this data set. We measure the S polarization anisotropy of the upper mantle using SKS splitting methods, control for possible non-lithospheric sources of splitting

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http://dx.doi.org/10.1016/j.tecto.2016.06.031
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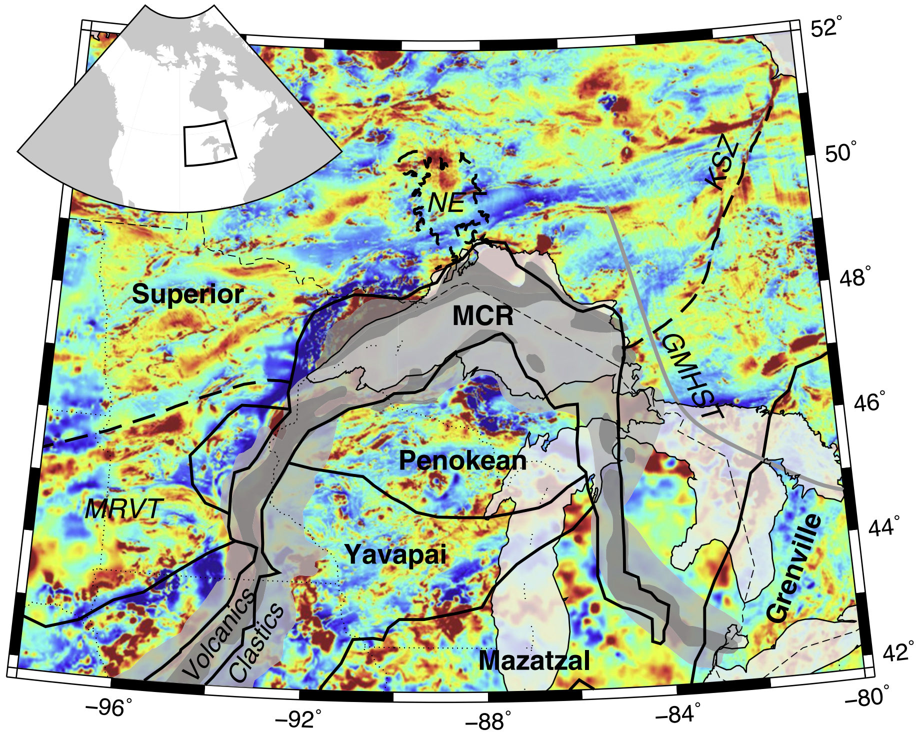

Fig. 1. Geologic setting of this study, overlain on a map of magnetic anomalies (North American Magnetic Anomaly Group, 2002). MCR: Mid-Continent Rift, MRVT: Minnesota River Valley Terrane, NE: Nipigon Embayment, KSZ: Kapuskasing Structural Zone, GMHST: Great Meteor Hotspot Track. Solid black lines are tectonic province boundaries from Whitmeyer and Karlstrom (2007); dashed lines are boundaries of interest within the Superior Province (MRVT boundary from Bickford et al. (2006); NE boundary from the National Atlas of Canada, http://atlas.gc.ca/site/english/maps/geology.html). Hotspot track is from Eaton and Frederiksen (2007). Shaded regions are clastic (lighter) and volcanic (darker) rocks associated with the MCR, from Ojakangas et al. (2001). Inset shows location of study within North America (box).

effects, interpret the measured splitting in terms of variations in lithospheric fabric, and examine the relationship between the MCR and the SP lithosphere. We suggest that rifting did not extend further to the north owing to the strong SP lithosphere, though MCR magmatism may have propagated into the Superior lithosphere in several places.

2. Tectonic and geophysical background

The Canadian Shield, the Precambrian core of North America, is an amalgam of Archean and Proterozoic tectonic blocks and orogens. The largest of the Archean blocks is the Superior Province, which stabilized ca. 2.6 Ga via accretion of a series of older terranes (Card, 1990; Calvert and Ludden, 1999; Percival et al., 2006). In the western Superior, these terranes form narrow belts with a consistent E-W alignment; sutures between these belts have been found to traverse the Moho in Lithoprobe seismic sections (White et al., 2003), indicating that tectonic accretion had a role in the formation of the Superior lithosphere. The lithosphere beneath the Superior Province is thick and seismically fast (Darbyshire et al., 2007; Frederiksen et al., 2007, 2013a) as well as strongly anisotropic (Darbyshire and Lebedev, 2009; Frederiksen et al., 2013b; Ferré et al., 2014), possibly as a result of accretionary processes. The lithosphere beneath the eastern Superior is seismically slower and contains an anomaly attributed to the Great Meteor hotspot track (Rondenay et al., 2000; Eaton and Frederiksen, 2007; Frederiksen et al., 2007). The eastern Superior was affected by uplift along the ca. 1.9 Ga Kapuskasing Structural Zone (KSZ; Percival and West, 1994).

The Superior Province is surrounded by Proterozoic orogens (Fig. 1). The oldest of these are the roughly contemporaneous Trans-Hudson and Penokean orogens, which accreted to the west and south of the Superior, respectively, ca. 1.8 Ga (Whitmeyer and Karlstrom, 2007). The Yavapai and Mazatzal orogens accreted further juvenile crust ca. 1.7 and 1.6 Ga, respectively, followed by extensive plutonism (Whitmeyer and Karlstrom, 2007; Amato et al., 2008). Further accretion continued southward with the Granite-Rhyolite Province ca. 1.55–1.35 Ga, which extends beyond our study area (Whitmeyer and Karlstrom, 2007). The last and largest of these orogens is the Grenville Orogen, which accreted to the east of the Superior in stages from 1.3 to 1.0 Ga as part of a major continent-continent collision (Davidson, 1998).

While Grenvillian orogenesis was in progress, a major magmatic feature cross-cut the preexisting Penokean, Yavapai and Mazatzal provinces: the Mid-Continent Rift (MCR). The MCR is a ca. 3000 km long, arcuate rift structure that curves through Lake Superior, with arms extending southwest and southeast (Van Schmus and Hinze, 1985; Ojakangas et al., 2001); rifting along the MCR may have been related to the opening of an ocean between Amazonia and Laurentia ca. 1.1 Ga (Stein et al., 2014). The rift contains large volumes of basaltic magma, generating a significant gravity anomaly (see, e.g., Merino et al., 2013); the high volume and geochemistry of the basalts suggest hotspot participation in the rifting process (Hutchinson et al., 1990; White, 1997; Hollings et al., 2010, 2012) and the MCR has been described as a hybrid of a rift and a large igneous province (Stein et al., 2015). A late compressional stage of the MCR's development may have reactivated structures related to the KSZ (Manson and Halls, 1997).

The Nipigon Embayment (NE; Fig. 1) is a magmatic feature north of Lake Superior, adjacent to the most sharply-curved section of the MCR. Its mafic and ultramafic rocks are contemporaneous with the early stages of the MCR (Hollings et al., 2007), but are predominantly emplaced in the form of sills rather than dykes. The dominance of sills is suggestive of a non-extensional tectonic regime (Hart and MacDonald, 2007), though sills are not in themselves incompatible with extensional processes. The NE has been found to overlie anomalous mantle in a number of studies (Ferguson et al., 2005; Frederiksen et al., 2007, 2013a).

Limited geophysical constraints are available on the lithosphere of the MCR. The MCR crust was examined by the Great Lakes International