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RESEARCH ARTICLE

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Key Points:

- A new, dense shear-wave splitting data set across the Mid-Continent Rift in Minnesota and Wisconsin
- Split times decrease southward, exhibiting a long-wavelength pattern that does not follow crustal tectonic boundaries
- The fast axis varies over short distances, with a narrow zone of northeast alignment following the rift axis

Supporting Information:

Supporting Information may be found in the online version of this article.

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Altered Mantle Fabric Beneath the Mid-Continent Rift

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Abstract We present new, densely sampled shear-wave splitting results from southern Minnesota and adjacent areas of neighboring states, sampling the southwestern limit of the Archean Superior Province and straddling the Proterozoic Mid-Continent Rift (MCR). The new measurements include data from the Earthscope Transportable Array (TA) as well as the Superior Province Rifting Earthscope Experiment (SPREE), yielding 99 new station-averaged measurements. The split times show a consistent decrease from 1.1 s in the NE to 0.2 s in the SW, with the lowest values being associated with the Minnesota River Valley Terrane (MRVT). From modeling and other geophysical constraints, we interpret the split time variations to represent variations in fabric strength within a thick lithosphere, rather than lithospheric thinning or a multi-layered effect, and propose that the weak fabric of the MRVT is associated with a different mechanism of formation than elsewhere in the Superior Province. The fast directions we measure range from NNE-SSW to E-W and vary on a shorter length scale than the split times, with a pattern of NE-SW splits that closely follows the axis of the MCR. We interpret this as a perturbation of the net fast direction due to anisotropy in an underplate along the rift.

Plain Language Summary This study presents new measurements of oriented fabric in the Earth's lithosphere, detected from variations in the polarization of seismic waves from distant earthquakes. These results are from southern Minnesota and the surrounding area, combining results from the national grid of Earthscope Transportable Array instruments with a denser deployment of portable instruments. The dense deployment was located so as to examine the Mid-Continent Rift (MCR), a billion-year-old region where stretching of the tectonic plate caused large amounts of volcanic rock to erupt. We found that the strength of fabric was largely unaffected by the MCR, even within the rift's boundaries, and instead varies according to the much older (around two and a half billion years old) regions predating it. The direction of the fabric, however, is influenced by the rift, with a consistent change in orientation that follows the rift axis. We interpret this effect as resulting from a layer of igneous rock that formed at the base of the crust during the rifting process.

1. Introduction: Tectonics of the Mid-Continent

Central North America was assembled in the Proterozoic from a series of Archean cratons and later orogens (Figure 1a; Whitmeyer & Karlstrom, 2007). The largest of these Archean blocks is the Superior Province, which assembled ca. 2.6 Ga from older terranes (Calvert & Ludden, 1999; Card, 1990; Percival et al., 2006). The southwest corner of the Superior Province is occupied by one of the oldest of these terranes, the ca. 3.5 Ga Minnesota River Valley Terrane (MRVT; Bickford et al., 2006), the northern boundary of which is defined by the Great Lakes Tectonic Zone (GLTZ). Post-accretionary deformation in the Superior was limited to uplift at ca. 1.9 Ga along a narrow region known as the Kapuskasing Structural Zone (KSZ; Percival & West, 1994). A series of Proterozoic orogens were then accreted to the Superior, beginning with the Trans-Hudson and Penokean orogens to the west and south ca. 1.8 Ga (Corrigan et al., 2005; Schulz & Cannon, 2007); subsequent accretion of the Yavapai and Mazatzal orogens onto the southern Superior took place ca. 1.7–1.6 Ga (Amato et al., 2008; Shaw, 1999). The most recent of these Proterozoic orogens to accrete to Laurentia is the Grenville Province, which formed by collision of Amazonia with Laurentia ca. 1.1–1.0 Ga but contains reworked older material (Easton, 1992; Hynes & Rivers, 2010).

Contemporaneously with Grenville accretion, the Mid-Continent Rift (MCR) cross-cut central North America ca. 1.1 Ga (Ojakangas et al., 2001). The MCR is an arc-shaped magmatic and sedimentary feature





Figure 1.

associated with strong gravity anomalies (Figure 1b), which exhibits the geometry of a continental rift and magma volumes typical of a large igneous province (Stein et al., 2015). The MCR consists of eastern and western arms that meet where the rift axis curves sharply through Lake Superior; the western arm shows stronger gravity highs consistent with either a greater magma volume (Merino et al., 2013) or lava flows being closer to the surface due to post-rifting inversion (Chandler et al., 1989), accompanied by deeper flanking basins that appear as gravity lows.

The tectonic history of this region has potential lithospheric consequences. Continental regions that have been stable since the Precambrian are typically associated with deep lithospheric roots, and those roots are typically of comparable age to the overlying crustal domains. However, continental rifting implies breakage of the continental lithosphere, while extensive magmatism from a mantle source implies either melting of the lithosphere or passage of an asthenospheric melt through a large thickness of solid material. Either of these processes would be expected to have long-lasting effects on the lithosphere, even if these effects may have been overprinted by later compression and inversion of the rift. A particularly good marker for lithospheric deformation and recrystallization is seismic anisotropy, which we apply here to a dense data set traversing the MCR.

2. The Mid-Continent Lithosphere

Central North America is underlain by a zone of fast upper mantle on continental-scale tomographic studies (see e.g., Bedle & van der Lee, 2009; Schaeffer & Lebedev, 2014; van der Lee & Frederiksen, 2005). Regional surface-wave studies of the Superior show that this cratonic root is approximately 200 km thick (Darbyshire et al., 2007), and is internally layered; the layering manifests largely as changes in anisotropy with depth (Darbyshire & Lebedev, 2008; Foster et al., 2020; Petrescu et al., 2017). Both velocity and anisotropy vary laterally in the vicinity of the MCR, with the rift's lower crust being visible as a low-velocity anomaly at short periods, and a strong high-velocity feature with east-west anisotropy underlying the western Superior at lithospheric periods.

Teleseismic body waves are more sensitive to laterally varying structure, at the expense of vertical resolution. Teleseismic *P* models of the midcontinent show a similar high-velocity feature beneath the western Superior, along with low-velocity features associated with MCR crust and Penokean syntaxes (Bollmann et al., 2019; Frederiksen, Bollmann, et al., 2013). The MCR is not consistently underlain by a lithospheric anomaly in either of these models, the most recent of which also includes data from the dense Superior Province Rifting Earthscope Experiment (SPREE) deployment (described in the next section). More localized receiver function analyses using the SPREE instrumentation (Chichester et al., 2018; Zhang et al., 2016) detected that the MCR axis is underlain by a doubled Moho, indicating the presence of a \approx 20 km thick layer interpreted to represent underplated material of basaltic composition. This underplate is confined to the vicinity of the MCR's gravity anomalies, and may also be responsible for the low-velocity features seen in surface and body wave models at lower-crustal depths (Bollmann et al., 2019; Foster et al., 2020).

A number of shear-wave splitting studies have examined mantle fabric in the midcontinent region. A large study by Yang et al. (2014) using primarily Earthscope Transportable Array instruments in the central US found high split times (>1.2 s) and fast directions parallel to the direction of absolute plate motion beneath the Superior, with split times reduced outside of the Superior. More focused regional studies found a higher degree of split time variation, with very low split times beneath the MRVT in southern Minnesota (Ferré et al., 2014; Frederiksen, Deniset, et al., 2013); a recent study by Ola et al. (2016) using SPREE data from Canada detected localized zones of weak splitting adjacent to the MCR, associated with the Nipigon Embayment and the Kapuskasing Structural Zone (KSZ). None of these studies, however sampled the MCR with sufficient density to allow unambiguous detection of the rift's influence on upper mantle fabric.

Figure 1. Tectonic setting of the Mid-Continent Rift (MCR) and environs. (a) Tectonic province boundaries (digitized from Whitmeyer and Karlstrom [2007]) overlain on a total-field magnetic map (North American Magnetic Anomaly Group, 2002). Gray shading indicates clastic and volcanic rocks associated with the MCR (digitized from Ojakangas et al. [2001]). MRVT, Minnesota River Valley Terrane; NE, Nipigon Embayment; KSZ, Kapuskasing Structural Zone; GMHST, Great Meteor Hotspot Track. (b) Seismometer coverage of the MCR region, overlain on a Bouguer gravity map (Tanner et al., 1988). Black inverted triangles are SPREE instruments (Wolin et al., 2015), gray inverted triangles are Earthscope Transportable Array (TA) instruments, gray upright triangles are other instruments from US and Canadian networks. Dashed box indicates the study area.





Figure 2. All events recorded by the SN, SM or SS lines judged to be of quality level 4 or greater for at least one station. Shading indicates at how many of these stations the event was of sufficient quality. The black region at center indicates the study area (43–47°N, 90–98°W). The map is centered on the midpoint of the SM line; circles represent 30° distance increments from this point.

3. Data

SPREE was a two-year deployment of 82 instruments from the Earthscope Flexible Array, targeting the western arm of the MCR and the north shore of Lake Superior (Figure 1b; Wolin et al., 2015). The instruments were deployed in four arrays: a sparse array instrumenting Ontario north of Lake Superior at a spacing comparable to the Earthscope Transportable Array (stations SC01-SC16), a dense line following the MCR axis through Minnesota (stations SM17-SM42), a northwest-southeast line crossing the MCR perpendicular to its axis in a zone where the gravity anomaly is broad (stations SN43-63 with SN51 omitted), and an eastwest line crossing a narrow portion of the MCR (stations SS64-SS83). The SPREE instruments were installed in the spring of 2011 and removed in the fall of 2013, in order to coincide with the Earthscope Transportable Array (TA) deployment in Minnesota.

In this study, we examine data from the dense portion of the SPREE deployment (the SM, SN, and SS lines) along with data from TA stations between 43–47°N and 90–98°W not previously analyzed using our methodology. Events falling in the 90–130° great-circle distance range (within which the SKS and SKKS pulses are expected to be well-separated from other arrivals) and with a minimum magnitude of 6 were considered for analysis, using the International Seismological Center (ISC) earthquake catalog (Bondár & Storchak, 2011). After quality control (described in the following section), we were left with a set of events covering the approximately 135° of back azimuth from southwest to north-northeast, as well as a scattering of events from the southeast (Figure 2). The event set varied for the TA stations, some of which were deployed and removed earlier or later than the SPREE stations. Data quality was generally good, though some SPREE stations occasionally lacked signal on one of the horizontal components; at station SM40, the north-south component was absent for

the majority of the recording period, and therefore insufficient usable data were obtained for analysis. We therefore report no results for this station.

One remarkable event, a magnitude 6.7 Papua New Guinea event (7.528°S, 146.814°E, 128.5 km depth), which occurred on December 14, 2011 at 5:04:58 UTC, displayed a high-quality SKS arrival at all stations. As shown in Figure 3, the particle trajectories of this event's SKS pulse are highly variable across the study area, with motion ranging from linear to strongly elliptical over short distances. This is direct evidence for short-wavelength variations in upper mantle anisotropy in the vicinity of the MCR.

4. Shear-Wave Splitting Analysis

Shear-wave splitting analysis is a well-established technique for detecting fabric in the upper mantle (see e.g., Long & Silver, 2009 for a review). An *S* wave entering an anisotropic medium will split into fast and slow quasi-*S* waves, which will separate in time as the wave travels; if the initial polarization is known (as it is for core-refracted phases like SKS), the time separation (known as the split time δt) and the azimuth corresponding to the polarization of the fast quasi-*S* pulse (known as the fast direction φ) may be measured using several possible techniques (see e.g., Kong et al., 2015; Silver & Chan, 1991; Wustefeld & Bokelmann, 2007). These two parameters amount to properties of an assumed single anisotropic layer, with the fast direction representing the orientation of horizontal fabric, and the split time representing a combination of intensity of fabric and thickness of the layer.

We perform single-event splitting measurements using the method of Silver and Chan (1991). Horizontal component traces are filtered in a 0.02–0.2 Hz passband, time windows around the SKS and SKKS arrivals are manually selected, and traces for which no clear SKS arrival is present are rejected. The resulting SKS and SKKS windows are then analyzed separately by performing a grid search over split times ranging from 0





Figure 3. Normalized particle motion plots for the SKS pulse on December 14, 2011 Papua New Guinea event. The purple lines indicate the trajectories traced out by the SKS pulse in the horizontal plane, as recorded at each station. The green arrow indicates the direction of travel of the incident wave. Note that this plot includes TA stations for which we do not report new measurements, due to the existence of published splits with comparable methodology.

to 3 s and fast directions ranging from 0 to 180° ; for each φ , δt pair, an inverse splitting operator is constructed and applied to the traces, reconstructing the corresponding incident traces. If the splitting parameters are correct, the incident traces should have linear particle motion in the radial direction; thus, a misfit may be calculated using either the energy of the reconstructed transverse component (a measure of deviation from radial polarization), or using the second-eigenvalue of the covariance matrix of the reconstructed traces (a measure of deviation from linear motion; Silver & Chan, 1991).

An example of this analysis is shown in Figure 4. The incident trace (Figures 4a and 4c) has elliptical particle motion (Figure 4b). The second-eigenvalue and transverse energy search grids are similar (Figures 4d and 4e), though their minima are slightly different (Figure 4f). When an inverse splitting operator is applied based on eigenvalue minimization, the recovered particle motion (Figure 4h) is highly linear, and the recovered fast and slow waveforms (Figure 4g) are very similar; the recovered incident wave has energy on the transverse component (Figure 4i), indicating that the most linear particle motion deviates from the radial direction. This could indicate deviation of the SKS raypath from the ray plane due to 3-D mantle structure.

It is important to note, however, that single-event splitting measurements are not particularly robust. The F-test used for error estimation (Silver & Chan, 1991) assumes perfect linear polarization of the incident wave, assumes a chi-square misfit, and requires a degrees-of-freedom calculation that can be fairly complex (Walsh et al., 2013); thus, the confidence contours in Figure 4f are likely to be inaccurate. Given that the SKS pulse likely contains scattered energy as well as a contribution from lowermost-mantle anisotropy, the most reliable information obtained from a single-event analysis is the regions of (Φ , δt) space for which the misfit is high (light-colored areas in Figures 4d and 4e).

Measurements averaged over multiple events are more reliable, particularly when the events sample a range of incident polarization directions. If the misfit surfaces (i.e., second-eigenvalue or transverse energy search grids) for multiple SKS observations are summed, the minimum of the stacked surface is effectively a joint inversion of the combined data set (Wolfe & Silver, 1998) which returns the single set of splitting parameters most compatible with the entire suite of waveforms. An alternative is to average the single-event splitting parameters, which can in some instances return higher split times that may be more reflective of a directionally varying fabric (Kong et al., 2015); error surface stacking and splitting parameter averaging are sufficiently different operations that averages from the two techniques are not directly comparable, particularly when the splitting is weak. As shown in the Supporting Information S1, averaging single-event split time



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Figure 4. Splitting analysis of the SKS pulse observed at SPREE station SM19 from the event in Figure 3; this trace was assigned a five on our five-point quality scale. (a–c) Band-passed SKS pulse recorded at SM19, shown as N-S/E-W components, particle motion in the horizontal plane, and radial/transverse components, respectively. (d and e) Error surfaces obtained by a grid search, using the second-eigenvalue and transverse energy criteria, respectively; darker shades represent more linear particle motion or lower transverse energy. (f) Best-fit splitting parameters and corresponding 95% confidence contours for the two misfit criteria. (g) Traces rotated into the best-fit (by eigenvalue) fast and slow direction. (h and i) Reconstructed incident wave, shown as horizontal particle motion and radial/transverse traces, respectively.

measurements will lead to an upward bias in the average when the true split time is low, while error surface stacking shows no such bias. In order to maintain consistency with past work, we select the eigenvalue error surface due to its robustness to variation in incident wave polarization, and apply a directionally balanced variant of error surface stacking (Frederiksen et al., 2007). In this approach, the error surfaces are stacked in 10° swaths by assumed incident polarization, the swath stacks are examined for directional consistency, and the swath stacks are stacked again with equal weight. Best-fitting splitting parameters are retrieved from the final combined stack, and a 95% confidence interval is calculated by treating the combined stack as a single-event measurement (thus overestimating the errors, but giving a value comparable from station to station). More detail on this procedure is given in Ola et al. (2016).

The reliability of shear-wave splitting measurements is greatly dependent on the quality control procedures used. We employ a qualitative approach in which individual SKS or SKKS measurements are rated on a five-point scale based on the noise level, the linearity of the recovered particle motion, the reduction of recovered transverse component energy, the tightness of the error contour, and the consistency between eigenvalue and transverse energy error surfaces. For the final stack, a minimum quality threshold was required for inclusion; at each station, we tested thresholds of 3, 4, and 5 on the five-point scale. We ultimately used a minimum quality threshold of 4, except for some stations from the SS line, for which a minimum threshold of 3 was used.

5. Results

We obtained 99 new shear-wave splitting measurements, from 65 SPREE and 34 TA stations. An average of 15 SKS and 6 SKKS measurements were retained at each SPREE station, while the TA stations returned an average of 12 SKS and 4 SKKS measurements. The SPREE stations gave an average fast direction of 65° and an average split time of 0.66 s, with average errors of 14° and 0.26 s, respectively; for the TA stations, the average fast direction and split time are 66° and 0.64 s, with errors of 12° and 0.23 s. Tables of these results are provided in the Supporting Information S1.

Figure 5 shows the variation of measured fast directions along great-circle transects N-N', M-M', and S-S', corresponding approximately to the SN, SM, and SS SPREE lines; stations within 30 km of the transect are included. Along the northern transect (N-N', Figure 5a), the fast direction is quite uniform at $\approx 65^{\circ}$, representing an ENE-WSW axis; there is a suggestion of a slight lessening trend (i.e., a counterclockwise axis rotation) southeastward along the transect, which is unlikely to be significant given the error bars. The absence of any change in orientation corresponding to the MCR axis is noted. The southern profile (S-S', Figure 5c) shows much greater variability, with measurements away from the MCR ranging from ≈ 70 to 100° (ENE-WSW to E-W), and measurements within or adjacent to the MCR axis ranging from 40 to 80° (NE-SW to ENE-WSW). The southward increase in scatter is clearly visible along the axis-parallel SM line (M-M', Figure 5b).

Along these profiles, the split times show less short distance variation and stronger large-scale trends (Figure 6). Most notable is a steady northward increase in split time along the SM line (Figure 5b), though a weaker eastward decrease is visible on both of the other lines. Split times along the SS line are smaller, have larger error bars, and are more scattered than along the SN line; no variation corresponding to the MCR axis is visible on the SS line, while on the SN line, a localized decrease in split time is visible immediately east of the rift axis.

A map of new and published shear-wave splits in the study area is shown in Figure 8. In the map area, published splits are drawn from Frederiksen, Deniset, et al. (2013), and Ola et al. (2016), which used the same measurement approach as this study, and Ferré et al. (2014), which used a comparable error surface stacking approach. The TA stations in the study area were also analyzed by Yang et al. (2014) using an event-averaging approach that is not directly comparable; for a comparison of our results and the Yang et al. results, see the Supporting Information S1.

Given that the fast direction variations in Figure 7 are fairly subtle, and accompanied by large changes in split time, the splitting parameters are best examined separately. The split time (Figure 8a) shows a systematic SW-NE increase, with the strongest splits (up to ≈ 1.2 s) occurring in the northeast corner of the study





Figure 5. Fast directions measured along transects roughly parallel to the (a) SN, (b) SM, and (c) SS SPREE lines. Larger circles with error bars are from this study; smaller squares without error bars are published results from previous studies (Ferré et al., 2014; Frederiksen, Deniset, et al., 2013; Ola et al., 2016). Shading indicates distance from great-circle transect, up to a maximum of 30 km; locations of the transects are shown in Figure 7.

area. The general trend of contour lines is WNW-ESE, though the 0.8 s contour is deflected parallel to the rift along the SN line. In the southern half of the study area, the greater scatter of the split times is reflected in a more complex pattern of contours. A large area of very weak (<0.5 s) split times is seen west of the MCR, centered at approximately 45°N, 95°W.

The fast directions (Figure 8b) show a more complex spatial pattern that varies over shorter distances. Broadly speaking, the pattern consists of four regions: a northwest zone with NE-SW axes (marked as A on the map), corresponding approximately to the Superior Province north of the GLTZ; a zone south of the GLTZ and west of the MCR (B), where fast axes are approximately E-W; a narrow zone following the MCR axis (C), with NE-SW axes; and a zone west of the MCR (D), with fast axes closer to E-W in orientation.

6. Discussion

6.1. Depth of Anisotropy

Teleseismic shear-wave splitting measurements do not, in principle, have depth resolution. Splitting of an SKS pulse can occur anywhere in the mantle or crust on the receiver side of the raypath. However, anisotropy in the mantle is largely restricted to the upper mantle and the D" layer just above the core-mantle boundary, with little in between (Romanowicz & Wenk, 2017); as discussed by Ola et al. (2016), anisotropy in D" will not be consistent between different back-azimuthal swaths and will be canceled out by our directionally balanced stacking procedure. We are therefore confident that the anisotropy we have detected lies above the transition zone.

Distinguishing between asthenospheric and lithospheric anisotropy requires that further assumptions be made. Anisotropy in the mantle is generally accepted to be controlled by lattice-preferred orientation of





Figure 6. Split times measured along transects roughly parallel to the (a) SN, (b) SM, and (c) SS SPREE lines. Larger circles with error bars are from this study; smaller squares without error bars are published results from previous studies (Ferré et al., 2014; Frederiksen, Deniset, et al., 2013; Ola et al., 2016). Shading indicates distance from great-circle transect, up to a maximum of 30 km; locations of the transects are shown in Figure 7.

olivine (Long & Becker, 2010), which is most strongly produced by dislocation creep; this mode of creep is favored above 200 km depth (Raterron et al., 2011), which may explain why anisotropy is strongest above \approx 250 km in anisotropic tomographic models (see e.g., Schaeffer et al., 2016). In central North America, the lithospheric thickness is greater than 200 km in multiple tomographic models (Steinberger & Becker, 2018), which would imply that the anisotropy we have observed is dominantly lithospheric. Given that the North American continental craton was assembled in the Archean and Proterozoic (Whitmeyer & Karlstrom, 2007), its lithospheric anisotropy is likely to be comparable in age.

Further constraints on the depth of anisotropy may be derived by considering the width of the Fresnel zone associated with an SKS arrival. The Fresnel zone is an approximate representation of the volume contributing to an arrival at a given frequency; Figure 7 shows Fresnel zones calculated for a ray length of 11,000 km, a frequency of 0.2 Hz, and various depths below the station. Given that structures with a horizontal scale smaller than the Fresnel zone diameter will be averaged over, short-wavelength variations in splitting parameters can be constrained to result from lateral changes in anisotropy at shallow depths. The pattern of split times we observe (Figure 8a) is large-scale and varies smoothly over the entire study area; as the Fresnel zone argument does not preclude a deep-rooted source for such long-wavelength variations, and given that split time is effectively cumulative along the raypath, we can with some confidence attribute the split time variations to variations in thickness or fabric strength of the entire lithosphere. Conversely, the fast direction (Figure 8b) varies over short distances, with feature C (associated with the MCR axis) being approximately 50 km across. As feature C is narrower than the SKS Fresnel zone at 100 km depth (Figure 7), it must reflect structure in the upper lithosphere only.

Another way to evaluate the depth of anisotropy is to compare splitting results to 3-D models. In Figure 9, our contoured results are overlain on 100 and 200 km depth slices through the teleseismic *P*-wave model of Bollmann et al. (2019). As both teleseismic *P* and SKS have near-vertical ray paths, the horizontal resolution





Figure 7. Map of shear-wave splitting results in the study area. Red symbols: this study; black symbols: previous studies using the same methodology (Frederiksen, Deniset, et al., 2013; Ola et al., 2016); gray symbols: results from Ferré et al. (2014), which used a comparable methodology. Arrow orientation indicates fast direction, while arrow length is proportional to split time. White circles indicate split times of 0.8 s or greater. Purple lines are tectonic boundaries from Figure 1a (dashed line is the GLTZ), while green dotted lines indicate the transects plotted in Figures 5 and 6. Background is shaded magnetics. The circles below the map indicate expected Fresnel zone widths for an SKS ray at given depths, in map scale.

characteristics of these measurements are comparable, while the depths of the *P* velocity structures are likely somewhat exaggerated by downward smearing. The 100 km depth slice (Figure 9a) shows a correlation between fast directions and velocities, with the contours of both trending SW-NE; in particular, zones B and C from Figure 8b correspond closely to a broad low-velocity anomaly, the strongest portion of which underlies the MCR axis (zone C). Split time contours are better correlated with the 200 km depth slice (Figure 9b), though the correspondence is weaker than for fast direction. Given these observations and the Fresnel zone argument, we interpret the large-scale split time pattern as deep-rooted (i.e., as a lithosphere-scale or asthenospheric feature), while the contrast between features B, C, and D must be shallow.

Finally, it is important to consider the possible effects of multiple layers, even though we are not able to resolve multi-layered effects in our data set. The apparent single layer splitting parameters resulting from multiple layers will vary with back azimuth and depend on the measurement method (Menke & Levin, 2003; Silver & Savage, 1994). It is also important to note that the effect of multiple layers is not the same for split time as for fast direction, in that fast direction shows more influence from the uppermost layer (Silver & Long, 2011). Thus, it is possible for the patterns of split time and fast direction to reflect structures averaged over different depth ranges. We model some specific two-layered scenarios later in this section.





Figure 8. Contour maps of (a) split time and (b) fast direction. Large circles are results from this study; smaller circles are previously published results. Contour intervals are 0.1 s and 5°, respectively. Thick gray lines are tectonic boundaries from Figure 1a; the dashed gray line is the GLTZ. Background shading is Bouguer gravity.

6.2. Split Time Variations: Thickness or Fabric Strength?

Although the short-wavelength fast direction variations we observe must be the result of fabric variations in the shallow lithosphere, the large north-south variations in split time across our study area are not so constrained. The Fresnel zone at the base of the lithosphere (ca. 200–250 km) is considerably smaller than the scale of split time variation (Figure 7) and so does not preclude an asthenospheric contribution to this phenomenon. Asthenospheric anisotropy is expected to correspond to the horizontal direction of simple shear resulting from its flow pattern, which is often taken to be parallel to the direction of absolute plate motion (APM). The absolute motion of the North American plate in the center of our study area is consistent over a wide range of models in both no-net-rotation and hotspot reference frames, averaging around 250° (UNAVCO, 2020); given the 180° symmetry of fast azimuths, this APM corresponds to a fast direction of 70°, which is within 20° of most of our measurements (Figure 8b), the exceptions being the cores of features A, B, and D.





Figure 9. Contours of (a) fast direction and (b) split time, overlain on shaded depth slices through the tomographic model of Bollmann et al. (2019). Depth slices are taken at (a) 100 and (b) 200 km depth, though note that the vertical smearing inherent in teleseismic tomography implies that structures are somewhat shallower than they appear.

There are, however, significant issues with attributing large portions of the observed split time to an asthenospheric contribution. Anisotropy is more efficiently produced by dislocation creep than diffusion creep, and diffusion creep is increasingly favored at higher temperatures and pressures (Long & Silver, 2009; Savage, 1999); though estimates of the depth of transition vary, 200 km is a common estimate (Miyazaki et al., 2013). Given that surface-wave models of the study area find the lithospheric thickness to be ca. 200 km (e.g., Schaeffer & Lebedev, 2014), dislocation creep and its accompanying anisotropy would be restricted to the lithosphere. In addition, it is difficult to explain how asthenospheric flow beneath a continent could be sufficiently laterally variable to produce the range of split times we detect, from 0.3 to 1.1 s, in a region where the expected asthenospheric flow would be highly uniform. We therefore interpret the majority of the observed split time to result from lithospheric fabric, though we cannot exclude a minor asthenospheric contribution.

Hypothesizing that the split times we observe are lithospheric in nature, we must then explain the large split time range observed. We will consider three possibilities for this: (a) variations in lithospheric thickness, (b) cancellation effects from multi-layered fabric, and (c) variations in fabric strength. With regard to the first of these possibilities, if the variation in split time were due to variable thickness of a uniformly anisotropic lithosphere, then a 200 km thick lithosphere corresponding to the 1.1 s split time region would have to thin to 54 km beneath the 0.3 s region, or even thinner than this if the higher splits north of our study area, which exceed 1.6 s in western Ontario, are taken into account (see e.g., Ola et al., 2016). Meanwhile, no such sharp lithospheric topography is seen in tomographic models (see e.g., Schaeffer & Lebedev, 2014; Yuan et al., 2014) or other seismic studies (e.g., Calò et al., 2016). We therefore feel confident in rejecting this hypothesis.

The second hypothesis to consider is multi-layered anisotropy causing cancellation of the splitting effect. There is evidence of both a mid-lithosphere discontinuity (Abt et al., 2010; Liu & Gao, 2018) and multi-layered anisotropy (Yuan & Romanowicz, 2010) in central North America. As noted in Section 4, we examined back-azimuthal variation in the error surfaces of our splitting analyses, finding that our results were consistent with the hypothesis of a single anisotropic layer; that does not mean, however, that multi-layered anisotropy can be ruled out entirely. To examine this possibility, we modeled a two-layered lithosphere in which the upper layer has a split time of 0.6 s and the lower 0.5 s, totaling the 1.1 s observed at the north end of our study area. For a given difference in angle between the fast azimuths of the two layers, we generated synthetic SKS pulses at back azimuths 10° apart covering the range of possible incident polarizations, and then performed SKS splitting analysis on the synthetic data set using the same methodology as real data. This complete back-azimuthal coverage is not achieved at any of our real stations, but represents what we would see given an ideal distribution of earthquakes, and should capture effects that are observable given good coverage.

The results of this modeling are shown in Figure 10. The results show that it takes a very high angle between the two fast axes to achieve strong cancellation, with values below 0.3 s only achieved when the two fast axes are in near-perfect opposition (80–90° apart). This is a very specific combination, and there is no evidence for such a strong contrast beneath the MRVT in anisotropic tomography or other data sets; we therefore consider cancellation by multi-layered effects to be an unlikely mechanism for the loss of observed anisotropy in southern Minnesota.

We are therefore left with our third hypothesis, large variations in the strength of lithospheric fabric, to explain the large range of split times we observe. Anisotropic fabric in continental lithosphere is typically assumed to be associated with past deformation, and may be very long-lived (Tommasi & Vauchez, 2015); in the western Superior Province, north of our study area, strong SKS splitting is parallel to tectonic fabric and has been interpreted as associated with Archean accretionary processes (Kay et al., 1999; Ola et al., 2016). The southwest quadrant of our study area, where our lowest split times were measured, corresponds approximately to the 3.5 Ga Minnesota River Valley Terrane (MRVT) of the Superior Province, although the boundary does not exactly match the crustal position of the GLTZ (Figure 8a). This observation was first made by Frederiksen, Deniset, et al. (2013) from sparser USArray data, who noted that the MRVT is old enough to potentially predate widespread plate tectonic processes, and therefore that it may have formed from vertical-tectonic processes that would not generate a horizontal lithospheric fabric. Ferré et al. (2014) confirmed the presence of low split time values in the MRVT, and described layered crustal fabric with a vertical symmetry axis, which would not contribute to shear-wave splitting; they also noted that there is no field evidence for a vertical-tectonics origin for the MRVT, and proposed a horizontally layered mantle as an alternative explanation for the low observed split times.

Our new data cannot resolve this issue in themselves, but do greatly improve the resolution of the split time contours. The 0.6 s contour line (Figure 8a) outlines the region we interpret as the lithospheric MRVT; it lies close to the crustal GLTZ at its northern limit, though its trajectory is more complex. The 0.6 s contour's deviations from the relatively straight crustal trace of the GLTZ suggest that the lithospheric boundary is



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Figure 10. Modeling results for a two-layer lithosphere with varying angles between the layers' fast directions. (a–e) Recovered one-layer error surfaces. Star: best-fit one-layer model; ×: upper layer; O: lower layer. Dotted lines indicate the single layer corresponding to perfect alignment of the two axes. (f) Best-fit one-layer split time plotted against the difference in fast axis azimuth; the dotted line marks 0.3 s, reflective of the very low split times found in southern Minnesota.

significantly different from the crustal line. Distinguishing between an isotropic MRVT fabric and one with a vertical symmetry axis (as suggested by Ferré et al. [2014]) would require a different type of anisotropic measurement, such as a comparison of Rayleigh and Love velocities at relevant periods in the MRVT.

6.3. Fast Axis Rotation Along the Mid-Continent Rift

The most novel feature seen in our measurements is coherent short-wavelength variation in the orientation of the fast axis (features B, C, and D in Figure 8b). As shown in Section 6.1, these variations must be shallow, that is, in the crust or shallow lithosphere. Feature B corresponds closely to the low split time zone associated with the MRVT, while feature D is associated with the northwest corner of the Yavapai Orogen. More dramatically, feature C has a remarkable correspondence with the axis of the MCR; the 65° fast axis contour closely follows both boundaries of the rift zone for 200–300 km.

P and *S* receiver function studies using SPREE data (Chichester et al., 2018; Zhang et al., 2016) independently detected a doubled Moho along the MCR axis, with ~25 km of material between the two interfaces. They interpreted this feature to represent an underplated layer of mafic composition related to the formation of the MCR. The underplate seen in receiver functions coincides with the MCR's positive gravity anomaly. Bollmann et al. (2019) also note that the low-velocity feature associated with feature C in the 100 km *P*-wave tomography slice (Figure 9a) has poor depth resolution, and could represent a downward-smeared anomaly from underplated material. As our observed feature C also closely follows the MCR gravity anomaly and is constrained to lie in the crust or upper lithosphere, we propose that feature C represents the influence of an underplated layer on the net observed shear-wave splits within the MCR.



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Figure 11. Modeling results for an underplated layer with a fast azimuth of 30° and varying split times. (a–e) Recovered one-layer error surfaces. Star: best-fit one-layer model; ×: underplated layer; O: underlying lithosphere. Dotted lines indicate the single layer corresponding to perfect alignment of the two axes. (f) Best-fit fast direction obtained for different underplate split times. The dotted line indicates a typical fast axis seen within the MCR.

We can test the plausibility of this proposal through modeling. If we assume that stations within feature C and adjoining areas of features B and D all sample the same lower lithosphere, for Fresnel zone reasons as discussed in Section 6.1, then in order for the fast direction to be altered by the underplate, the underplated material must be anisotropic and have a different fast direction than the underlying lithosphere. For modeling purposes, we rather arbitrarily assumed that the underplated layer has a fast axis roughly parallel to the rift axis (30°) overlying a lithospheric layer with a fast axis of 75° and a split time of 0.5 s. We then modeled the effective splitting parameters for the two-layer combination, in the same manner as in Section 6.2, for different split time values in the underplated layer (Figure 11). The modeling results indicate that a split time of 0.30–0.35 s in the underplated layer is required to produce a net fast direction of 60°; a split time of 0.35 s in a 25 km thick layer with a fast direction *S* velocity of 4.2 km/s (value from Chichester et al. [2018]) implies a slow direction velocity of 4.0 km/s, representing an *S* velocity anisotropy of 5.5%. This value is not unreasonable for foliated gabbroic material (Ji et al., 2014).

We obviously lack sufficient constraints to directly detect multiple anisotropic layers beneath the MCR axis, but our modeling shows that anisotropy in underplated material beneath the MCR axis can explain the observed small-scale changes in fast direction. More detailed constraints on layered anisotropy beneath the MCR will require the use of methods with depth resolution, such as ambient noise analysis or anisotropic inversion of receiver functions.

7. Conclusions

We have presented a large new data set of shear-wave splits derived from SKS and SKKS pulses recorded at SPREE and Transportable Array stations in southern Minnesota and adjacent areas, spanning the western arm of the MCR. We found spatially coherent variation at multiple scales, with split times ranging from 0.2



to 1.1 s and fast axes ranging from NNE-SSW to E-W. The split times vary on a larger spatial scale than the fast directions, with a dominant NE-SW decrease to very low values in the MRVT. We attribute this drop to a lack of horizontal fabric in the lithosphere of this terrane compared to other Superior Terranes, reflecting a different mode of formation of the crust and lithosphere. The fast directions are perturbed along the MCR axis on a short length scale; we interpret this to represent the effect of differing anisotropy within an underplated layer that is confined to the rift axis.

Data Availability Statement

All data used in this study are available from the IRIS Data Management Center under network codes SPREE-XI and TA-TA. Full tables of SKS splitting results are provided in the Supporting Information S1.

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