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Key Points:

- The Archean crust of the Minnesota River Valley is strongly anisotropic
- The horizontally layered crust of the MRV cannot split vertical shear waves
- The cause of low SWS in the MRV must be in the uppermost mantle

Supporting Information:

- Readme
- Figure S1
- Tables S1-S3

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Seismic anisotropy of the Archean crust in the Minnesota River Valley, Superior Province

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Abstract The Minnesota River Valley (MRV) subprovince is a well-exposed example of late Archean lithosphere. Its high-grade gneisses display a subhorizontal layering, most likely extending down to the crust-mantle boundary. The strong linear fabric of the gneisses results from high-temperature plastic flow during collage-related contraction. Seismic anisotropies measured up to 1 GPa in the laboratory, and seismic anisotropies calculated through forward-modeling indicate ΔV_P ~5–6% and ΔV_S ~3%. The MRV crust exhibits a strong macroscopic layering and foliation, and relatively strong seismic anisotropies at the hand specimen scale. Yet the horizontal attitude of these structures precludes any substantial contribution of the MRV crust to shear wave splitting for vertically propagating shear waves such as SKS. The origin of the regionally low seismic anisotropy must lie in the upper mantle. A horizontally layered mantle underneath the United States interior could provide an explanation for the observed low SWS.

1. Introduction

Seismic anisotropy in continental areas originates primarily from lattice preferred orientation (LPO) in the mantle and the crust [e.g., *Karato*, 1987; *Nicolas and Christensen*, 1987; *Mainprice and Silver*, 1993]. Seismic anisotropy has received considerable attention because it informs both active motion and ancient deformation of lithosphere/asthenosphere on a scale that is only matched by active displacement fields of active tectonic regions from geodetic data (Global Positioning System). However, the timing and specific mechanisms resulting in LPO in the continental crust remain far less understood than that in the oceanic lithosphere. [e.g., *Fountain and Christensen*, 1989; *Kern*, 1990; *Silver and Chan*, 1991; *Barruol and Mainprice*, 1993; *Silver*, 1996; *Savage*, 1999; *Eaton and Jones*, 2006].

Seismic anisotropy in the upper mantle arises primarily from olivine and pyroxene LPO acquired through plastic flow [*Hess*, 1964; *Peselnik et al.*, 1974; *Fuchs*, 1977; *Christensen*, 1984; *Karato*, 1987; *Nicolas and Christensen*, 1987; *Mainprice and Silver*, 1993]. In contrast, the origin of crustal seismic anisotropy is more elusive [*Mainprice and Nicolas*, 1989; *Ozacar and Zandt*, 2004; *Shapiro et al.*, 2004; *Christensen and Mooney*, 1995; *Barruol and Kern*, 1996; *Fouch and Rondenay*, 2006]. Crustal seismic anisotropy may be related to minerals LPO, like in the mantle, or with metamorphic layering, aligned cracks, or some combination of these structures.

Within continental areas, some cratonic domains display large seismic anisotropies and hence constitute legitimate targets to investigate the origin and significance of anisotropy. Archean provinces such as the Superior Province, the Sao Francisco Craton, or the Kaapvaal Craton show some of the largest splitting delay times, $\delta t \approx 1.5$ s, observed on continents [e.g., *Vinnik et al.*, 1995; *James and Assumpção*, 1996; *Barruol et al.*, 1997]. These provinces also exhibit large internal variability in the fast seismic directions [e.g., *Waite et al.*, 2005]. Together with their correlation with the orientation of surface tectonic features, these variations suggest that crustal domains were assembled by the amalgamation of microplates [e.g., *De Wit et al.*, 1992].

The most routinely determined measure of seismic anisotropy is from shear wave splitting. Splitting of teleseismic shear waves such as SKS waves results from integration of anisotropy from the core-mantle boundary to the Earth's surface. Because the mantle portion of the raypath is much longer than the crustal portion, researchers often discount the crust as a major contributor to shear wave splitting observations.

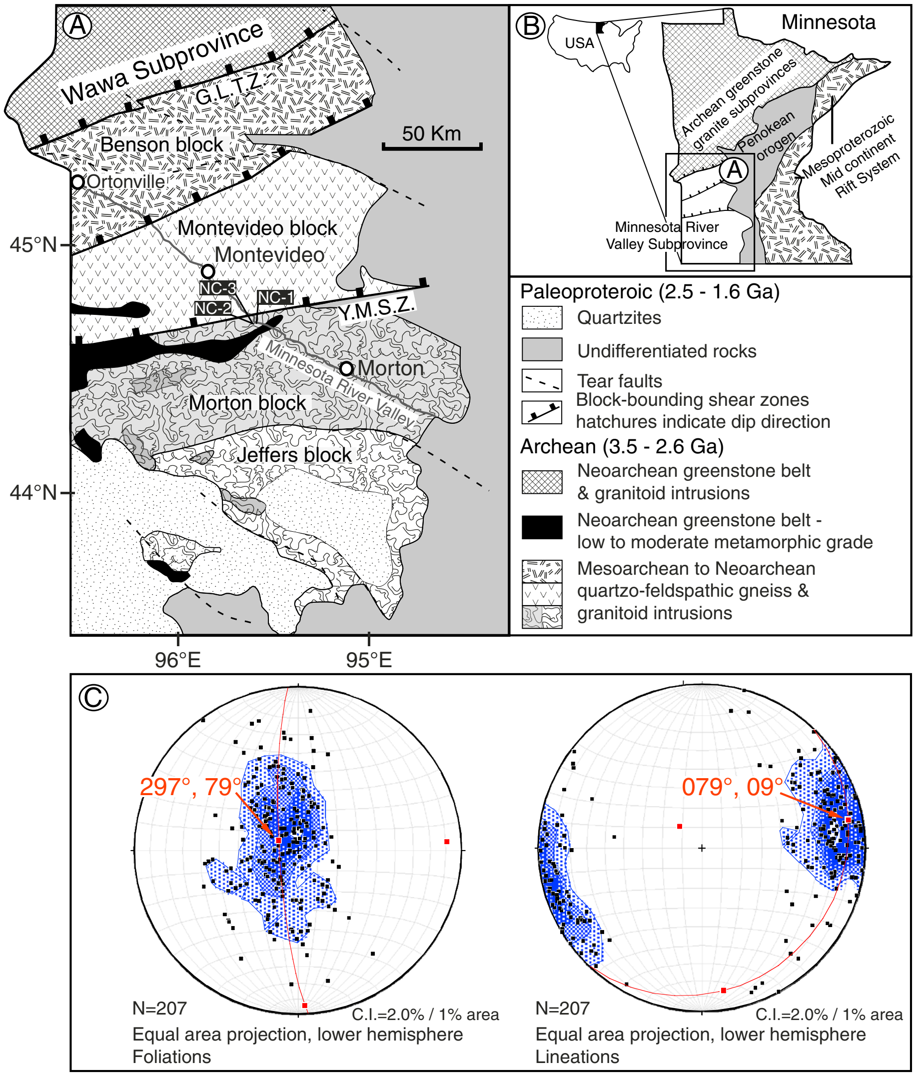

Figure 1. (a) Simplified bedrock geological map of the Minnesota River Valley (MRV) subprovince, showing major crustal-scale shear zones [*Schmitz et al.*, 2006]. (b) Box outline of Figure 1a. (c) Stereonets, lower hemisphere, equal area projection of anisotropy of magnetic susceptibility for Morton gneisses [*Ferré et al.*, 2003].

While much of the Superior Province exhibits splitting times greater than 1 s [*Barruol et al.*, 1997; *Gao et al.*, 1997; *Frederiksen et al.*, 2007, 2013], surprisingly, splitting times in the Minnesota River Valley (MRV) are closer to a few tenths of a second [*Frederiksen et al.*, 2013]. Total splitting times of a few tenths of a second require a careful accounting of crustal anisotropy for reliable interpretation.

Here, we investigate the origin and tectonic significance of seismic anisotropy in the Archean lower crustal rocks exposed in the MRV. We combine direct laboratory measurements, petrofabric analysis, and forward modeling of rock elastic properties that can be translated in terms of anisotropy of teleseismic shear wave propagation. The measured and predicted seismic anisotropies are then used to quantify the respective contributions of the crust and upper mantle to splitting delay times.

2. Tectonic Setting of the Minnesota River Valley Complex, Superior Province

The Superior Province, an Archean craton, forms the core of the North American continent [e.g., *Hoffman*, 1989; *Card*, 1990; *Darbyshire et al.*, 2007]. This province consists of terranes amalgamated along WSW-ENE trending shear zones (Figure 1). The Minnesota River Valley constitutes one of the best exposed sections of late Archean continental lithosphere in the Superior Province. It consists primarily of high-grade, coarse-grained, and layered gneisses metamorphosed in the upper amphibolite to granulite facies. This metamorphic package of Archean rocks forms the autochton of Proterozoic units to the North. Across the four tectonic blocks of the MRV, gneissic rocks consistently display a subhorizontal layering and a subhorizontal foliation. COCORP seismic reflection profiles suggest that this persistent broadly horizontal tectonic fabric most likely extends down to the crust-mantle boundary to a depth of 45–51 km [*Gibbs et al*., 1984]. The MRV Complex constitutes the southernmost subprovince of the Superior Province [e.g., *Southwick and Chandler*, 1996]. To the north, the shallowly north dipping Great Lakes Tectonic Zone (GLTZ) separates the MRV from the Wawa Subprovince [Figure 1, *Gibbs et al*., 1984; *Southwick and Chandler*, 1996]. The MRV subprovince shows a layered crust-mantle transition at 45–51 km depth [*Gohl et al*., 1993], possibly corresponding to a "magmatic underplating" type of Moho [*Eaton*, 2006]. The thickness of the crust is slightly above the average for Archean crusts and also appears consistent with basaltic underplating [*Durrheim and Mooney*, 1991]. The average crustal P wave velocity ranges from 6.5 to 7.0 km/s, while the base of the crust shows higher velocities that range from 6.8 to 7.5 km/s [*Southwick and Chandler*, 1996]. Seismic refraction surveys indicate rapid variations in thickness, at the scale of a few km across the tectonic grain [*Braile*, 1989]. The MRV consists of four juxtaposed Archean crustal blocks, the Benson, Montevideo, Morton, and Jeffers blocks from north to south (Figure 1). Abundant and fresh exposures along the MRV consist of quarries and glacier-polished outcrops, while Late Cretaceous sedimentary rocks and Quaternary glacial deposits cover the rest. While exposures are limited to the river valley, potential field geophysics provides a three-dimensional view of these rocks [*Southwick and Chandler*, 1996].

The four blocks of the MRV host broadly similar rock types, mainly quartzo-feldspathic migmatites with minor tonalitic, granodioritic, dioritic, and pelitic layers that grade into each other. The northernmost Benson block hosts more plutonic material than the other three blocks to the south, including tonalites, quartz diorites, and granodiorites with well-preserved igneous microstructures. The Montevideo and Morton blocks preserve Mesoarchean crustal segments that were deformed and metamorphosed during Neoarchean accretion of the MRV subprovince to the southern Superior Province. The migmatitic gneisses of the Morton block appear slightly more leucocratic than the rocks of the other blocks. These gneisses host amphibolite horizons interpreted as boudinaged tholeiitic basalt sills [*Nielsen and Weiblen*, 1980]. These four blocks differ in their geophysical properties [*Southwick and Chandler*, 1996], such as average rock density (Benson: $\rho = 2750$ kg/m^3; Montevideo: $\rho = 2860$ kg/m^3; Morton: $\rho = 2760$ kg/m^3; Jeffers: $\rho = 2750$ kg/m^3) and aeromagnetic anomalies, with the southernmost Jeffers block showing larger aeromagnetic anomalies than the other three blocks. The post-tectonic intrusions emplaced throughout the high-grade gneisses of the MRV might correspond to the granite "blooms" interpreted by *Percival and Pysklywec* [2007] as a result from lithospheric keel inversion.

The metamorphic foliation throughout the MRV is subparallel to a centimeter-scale to millimeter-scale compositional layering and generally shows shallow dips ($<20°$). Mineral lineations and stretching lineations in these high-grade gneisses are scarce and parallel to gently plunging fold axes [*Bauer*, 1974, 1980]. The anisotropy of magnetic susceptibility (AMS) of the Morton migmatite records a high-temperature plastic fabric characterized by a subhorizontal foliation and a N080° trending subhorizontal lineation [Figure 1c; *Ferré et al*., 2003, 2004]. The four blocks of the MRV are separated by WSW-ENE linear gravity and magnetic anomalies, some of which, like the Yellow Medicine Shear Zone (YMSZ), are regional north dipping shear zones (Figure 1). The YMSZ, separating the Montevideo and Morton blocks, was reactivated during the Penokean orogeny 2.45–1.75 Ga [*Goldich and Wooden*, 1980a, 1980b; *Southwick and Chandler*, 1996]. Historic seismicity is preferentially localized along block boundaries, which suggests that they may underline major lithospheric discontinuities [*Mooney and Morey*, 1981; *Chandler*, 1994].

Amphibolite- to granulite-facies assemblages have been reported by *Himmelberg and Phinney* [1967] and *Goldich et al*. [1980a, 1980b]. Goldich et al. established the Archean age of the MRV basement [*Goldich et al*., 1970, 1980a, 1980b; *Goldich and Hedge*, 1974; *Goldich and Wooden*, 1980a, 1980b]. Recent ion microprobe (SHRIMP) and ID-TIMS U-Pb zircon data have further constrained the 3.42 to 3.52 Ga protolith ages of tonalitic to granitic gneisses in the Morton and Montevideo blocks [*Bickford et al*., 2006; *Schmitz et al*., 2006]. Both blocks subsequently experienced igneous and metamorphic overprints at ca. 3.38, 3.14, and 2.60 Ga. The timing of accretion of the MRV terranes to the southern Superior province was constrained by *Schmitz et al*. [2006], who used high-precision U-Pb monazite and zircon ages to date granulite-facies metamorphism at ~2.6 Ga. This metamorphism coincides with voluminous late- to post-kinematic granitoid intrusion, which those authors tentatively related to crustal melting resulting from collisional thickening of colliding MRV crust.

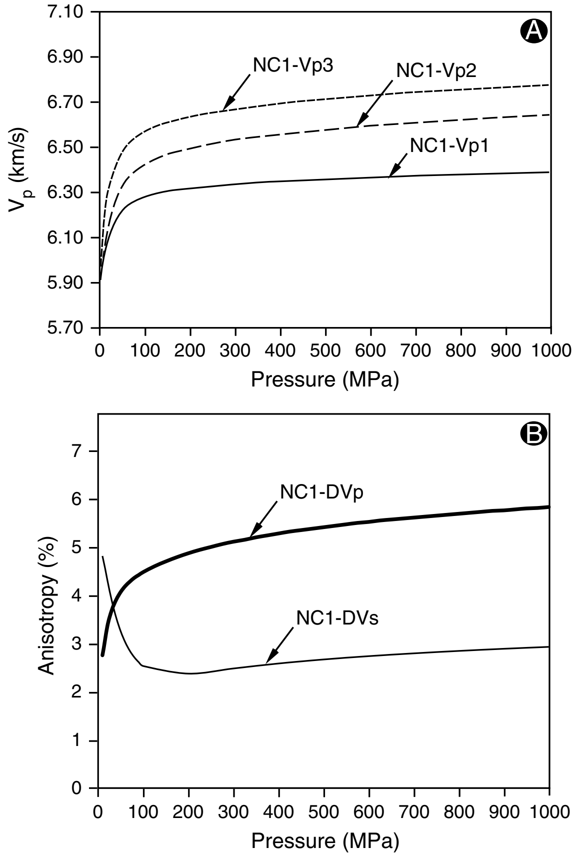

Figure 2. (a) *P* wave seismic velocity (km/s) as a function of confining pressure (MPa) measured in the laboratory for sample NC1 along three mutually perpendicular directions. (b) Seismic wave anisotropy measured in the laboratory on sample NC1 as a function of confining pressure up to 1 GPa. ΔV_P (bold line) shows an initial fast increase in anisotropy caused by crack closure, followed by a steady, near linear increase as a function of pressure, up to 5.8% at 1 GPa. ΔV_S (normal line) displays an initial decrease in anisotropy up to 150 MPa, followed by a steady increase up to 2.8% at 1 GPa.

3. Laboratory Velocity Measurements

We performed measurements in the petrophysics laboratory at the University of British Columbia, following the procedure of *Christensen* [1971]. Samples were trimmed and polished to right circular cylinders with flat, parallel ends. Sample densities were determined from the volumes and weights of the rock cores. Velocities from single cores were measured as a function of confining pressure using the pulse transmission technique [*Birch*, 1960; *Christensen*, 1985]. First break picks for acquired waveforms are automatically selected by a computer interfaced with the pressure system. The estimated error in the velocities is 0.5%.

The mineral percentages given in the supporting information were obtained by point counting 1000 grains from each sample. These counts are from a single thin section and thus may not adequately represent the banded specimens. Sample NC1 is a quartzo-feldspathic biotite gneiss, and sample NC3 is a hornblende plagioclase gneiss, both with amphibolite-facies mineralogies. NC2 is a mafic granulite facies gneiss.

For NC-1, NC-2, and NC-3, we obtained average densities of $\rho = 2756$, 3074, and 2982 kg/m^3, respectively; compressional wave seismic velocities of $V_P = 6.556$, 6.843, and 6.695 km/s at 550 MPa, a pressure equivalent to a depth of 20 km; and average seismic anisotropies of $\Delta V_P = 5.47$, 4.31, and 2.35% (with $\Delta V_P = 100(V(90°) - V(0°)) / 1/2(V(90°) + V(0°))$. We consider NC-1 the most representative sample for the Morton block because its measured density $\rho = 2756$ kg/m^3 is near the average density of the Morton block [$\rho = 2760$ kg/m^3; *Chandler and Lively*, 2003]. These results also indicate that up to a depth of approximately 7 km, corresponding to 200 MPa, the MRV rocks are likely to display a V_P anisotropy partially controlled by cracks and fractures. Below 7 km, the main contribution to crustal anisotropy would result primarily from rock fabric.

Compressional (V_P) and shear (V_S) wave velocities at hydrostatic pressures up to 1 GPa (equivalent to approximately 35 km depth) are reported as supporting information for three representative samples of Archean gneisses collected from the Morton block (locations shown in Figure 1). For each sample, compressional wave velocities were measured for three cores taken in mutually perpendicular directions, one normal to the layering (144° NE 15°) and two in the plane of the layering, one of these being parallel to the mineral lineation (070°, 15°). V_P in supporting information is given for all the three measurements, and the average is shown in Figure 2a. Two shear wave velocities were measured for propagation in the layering planes and parallel to the sample lineations. V_{S1} is the fast shear wave vibrating parallel to the layering, and V_{S2} is the slow shear wave vibrating normal to the layering. For most rocks, this birefringence is a measure of maximum shear wave splitting (Figure 2b). The measured anisotropies take into account the orientations of several hundred thousand grains [*Christensen*, 1985] and the elongated and platy grain shapes of hornblende and biotite, which are the minerals primarily responsible for the anisotropies. At pressures below 200 MPa, oriented grain boundary cracks affect the anisotropies.

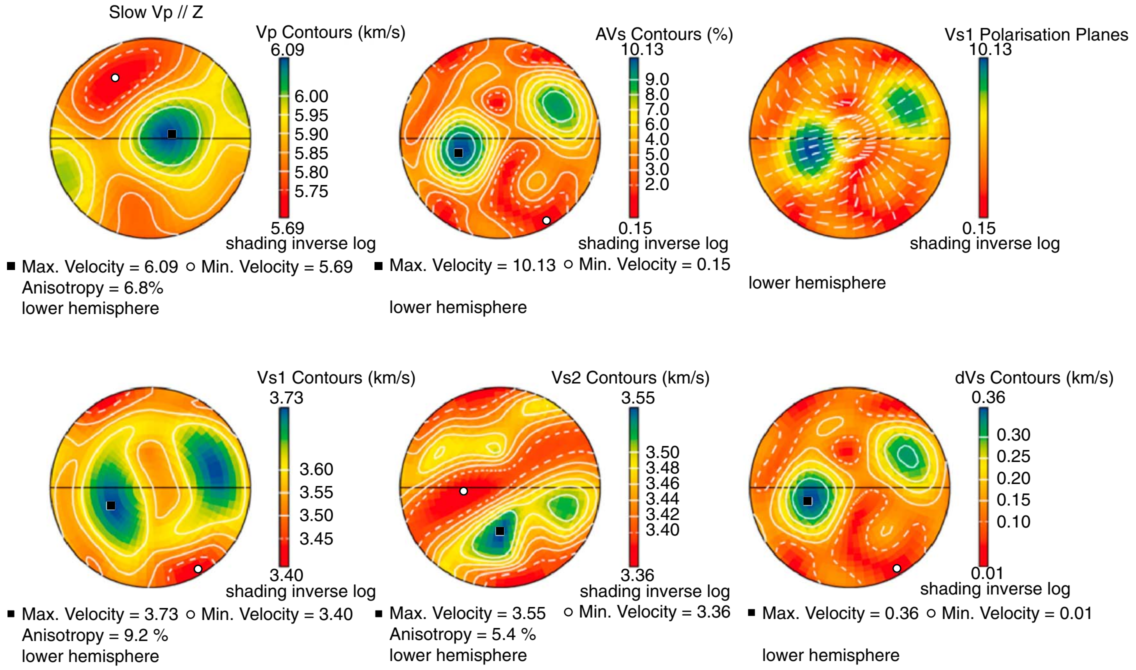

Figure 3. Forward modeling of seismic properties calculated for a biotite gneiss (212C) from LPO and mineral elastic constants. V_{PX}, V_{PY}, and V_{PZ} are the compressional wave velocities measured in the specimen finite strain reference framework where X is the lineation and Z is the pole to foliation.

The importance of the shear measurements is twofold. The measurements clearly demonstrate that the rocks produce splitting and more importantly give us an estimate of the maximum splitting for each sample. Previous studies of similar rocks at hydrostatic pressures to 1000 MPa [e.g., *Christensen*, 1966; *Godfrey et al.*, 2000], triaxial compression to 600 MPa [e.g., *Kern et al.*, 1997], and calculations using measured lattice preferred orientations of crustal minerals and their elastic properties at atmospheric pressure [*Barruol and Mainprice*, 1993] have shown that the magnitude of shear wave splitting decreases to almost zero as the propagation direction varies from the plane of the layering to the layering normal. Thus, for vertical propagation in the crust, steeply dipping layering will produce maximum splitting, and horizontal layering will result in minimum splitting. Calculated maximum splitting times for a 10 km crustal section with vertical layering, using velocities at mid-crustal pressures, are 0.07, 0.08, and 0.05 s for NC-1, NC-2, and NC-3. Variations of the layering from vertical will produce significantly lower split times.

4. Forward Modeling of Seismic Properties Based on Lattice Preferred Orientation (LPO)

We used the elastic properties of constituting mineral phases together with their LPOs determined by electron backscatter diffraction to calculate the directional seismic properties of two representative oriented gneisses. Details of this forward modeling method are described in *Mainprice* [1990] and *Mainprice and Humbert* [1994]. Modal compositions were determined by point counting on the same thin sections used for LPO measurements. We use published elastic data for quartz [*McSkimin et al.*, 1965; *Calderon et al.*, 2007; *Lakshtanov et al.*, 2007], alkali feldspar [*Brown et al.*, 2006], plagioclase [*Carpenter*, 2006], biotite [*Simmons and Wang*, 1971], and hornblende [*Aleksandrov and Ryzhova*, 1961; *Bass*, 1995; *Isaak*, 2001; *Ji et al.*, 2002].

Biotite-gneiss 212C consists of plagioclase [An_{24}] (61.4%), quartz (28.2%), and biotite (10.3%). The maximum anisotropy for *P* waves is 6.8%, with $V_{PY} > V_{PX} > V_{PZ}$ (Figure 3). Shear wave splitting (SWS) is highest in the foliation plane, a typical feature of biotite-dominated seismic properties, with the fastest polarization in the foliation plane. Hornblende-gneiss 212G consists of plagioclase [An_{24}] (71.4%), quartz (11.8%), and hornblende (17.0%). The maximum anisotropy for *P* waves is 5.4%, with $V_{PZ} > V_{PY} > V_{PX}$. SWS is complex, a typical feature of plagioclase-dominated seismic properties.

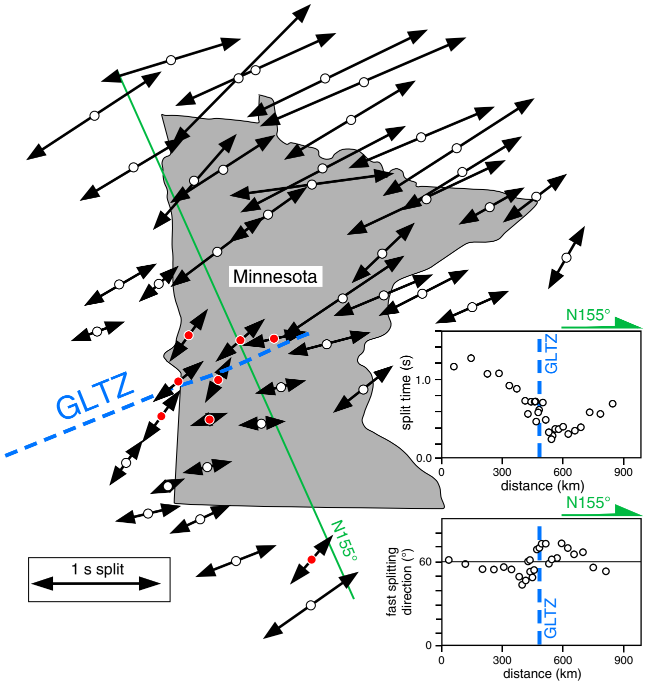

Figure 4. Summary of shear wave splitting (SWS) results for Minnesota and surrounding regions. New data (with red dots) merged with *Frederiksen et al.* [2013]'s SWS data. The Great Lakes Tectonic Zone (GLTZ) constitutes a lithospheric block boundary across which seismic anisotropy decreases rapidly from north to south. The splitting directions differ on either side of the GLTZ.

These results indicate that, in rocks dominated by plagioclase such as the gneisses of the MRV where plagioclase accounts for 40 to 80% in volume [*Goldich et al.*, 1980a, 1980b], small variations in Plag-Bt-Hbl volume fractions control the seismic properties. These results also show that ≈10% of biotite, or ≈70% of plagioclase or ≈20% of hornblende would be capable of controlling bulk rock seismic properties. Overall, the seismic properties of mid- to lower crustal rocks depend primarily on the percentage of elastically anisotropic phases such as biotite or hornblende and to a lesser degree on the percentage of quartz and feldspars in the granulite- and amphibolite-facies Archean crust.

In the Morton block, the average magnetic lineation (N079°, 09°) and the forward modeled seismic anisotropy (N070°, 20°) have broadly similar azimuth. Since the magnetic fabrics in the MRV originated from high-temperature plastic flow during regional deformation [*Ferré et al.*, 2003], it seems likely that the same deformation process would also control the development of crustal anisotropy at a larger scale. To test this hypothesis, in the following, we investigate teleseismic anisotropy.

5. Shear Wave Splitting in the Minnesota River Valley

To more fully examine the seismic anisotropy across the MRV, we augment the results of *Frederiksen et al.* [2013] with SWS measurements of SKS waves using SplitLab [*Wüstefeld et al.*, 2008] for several USArray stations in the MRV. Our results, shown with red dots in Figure 4, are consistent with *Frederiksen et al.* [2013] in that we see a noticeable drop in splitting time as well as significant changes in fast direction over short distances in the MRV relative to surrounding craton. South and north of the MRV, splitting times tend to be >1 s and exhibit fast direction ~N050°–060°, parallel to the absolute plate motion direction [*Frederiksen et al.*, 2007]. In the MRV, splitting times are typically <0.5 s and indicate an anomaly in splitting directions around the GLTZ (Figure 4). V_S anisotropy for the Morton block hornblende gneiss would be almost nul for a vertically travelling *S* wave in a horizontally layered medium, as shown by previous studies elsewhere [e.g., *Godfrey et al.*, 2000].

6. Discussion and Conclusions

At the outcrop scale, the MRV Archean gneisses display a strong nearly horizontal macroscopic and magnetic planar fabric [*Bauer*, 1974; *Ferré et al.*, 2003, 2004]. The same rocks also exhibit a consistent macroscopic and magnetic linear fabric (Figure 1), interpreted as resulting from high-temperature plastic flow. The AMS recorded in the MRV high-grade gneisses preserves information on high-temperature deformation despite significant post-kinematic annealing, as described in granitic rocks elsewhere [*Ferré and Améglio*, 2000]. These linear fabrics, parallel to the MRV N075° block boundaries, most likely originate from collage-related tectonics during the MRV subprovince late-Archean assembly. The MRV terrane, with its gently north-dipping block boundaries, subsequently reactivated as transcurrent shear zones like the Yellow Medicine shear zone, shares striking similarities with the Limpopo Belt separating the Kaapvaal craton from the Zimbabwe craton [e.g., *Silver et al*., 2004].

The MRV crust exhibits a strong macroscopic fabric, represented by compositional layering and foliation, and relatively strong seismic anisotropies at the hand specimen scale. Yet despite these significant anisotropies, the horizontal attitude of these structures precludes any substantial contribution of the MRV Archean crust to SWS. The origin of the regionally low seismic anisotropy must therefore lie in the mantle, although it is emphasized that the crust is significantly anisotropic and will produce strong shear wave splitting for horizontal wave propagation. The total crustal delay time has been estimated to be 0.1 s in other regions using Moho-converted PmS phases [*McNamara and Owens*, 1993]. The vertical tectonics hypothesis proposed by *Frederiksen et al*. [2013] is not supported by any structures in the field. One would expect diapiric tectonics to be expressed in map patterns similar to those of the Chindamora Batholith of Zimbabwe [e.g., *Ramsay*, 1975], and this is not the case [*Southwick*, 2002].

The concept of a horizontally layered mantle underneath the United States interior [*Yuan and Romanowicz*, 2010] could provide an explanation for the observed low SWS if two superimposed mantle layers contributed destructively to seismic anisotropy.

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