# Characteristics of mantle fabrics beneath the south-central United States: Constraints from shear-wave splitting measurements

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## ABSTRACT

New shear-wave splitting measurements at permanent broadband seismic stations in the south-central United States reveal the orientation and degree of polarization of mantle fabrics, and provide constraints on models for the formation of these fabrics. For stations on the stable North American craton, correspondence between observed polarization direction of the fast wave and the trend of Proterozoic and Paleozoic structures associated with rifts and orogenic belts implies a lithospheric origin for the observed anisotropy. The largest splitting times (up to 1.6 s) are observed at stations located in the ocean-continent transition zone, in which the fast directions are parallel to the Gulf of Mexico continental margin. The parallelism and the geometry of the keel of the craton beneath the study area suggest that asthenospheric flow around the keel of the North American craton, lithospheric fabrics developed during Mesozoic rifting, or a combination of these factors are responsible for the observed anisotropy on stations above the transitional crust.

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**Keywords:** shear-wave splitting, seismic anisotropy, continent-ocean transitional crust, mantle flow, south-central United States.

## INTRODUCTION

The ocean-continent transition is the lithospheric substrate to a passive margin, the site of broad sedimentary out building, and the likely home of most of the world's undiscovered hydrocarbon deposits. The nature of ocean-continent transition crust and the transitional lithosphere is controversial, and there are fundamental unresolved questions. For example, recent studies of the Vøring Plateau offshore Norway (Fernández et al., 2004; Mjelde et al., 2007) suggest that the ocean-continent transition may be narrow, but that there is a broad zone in which the oceanic and stretched continental crust were ultimately thickened by massive mafic underplating to form a volcanic rifted margin. In other cases, such as the Iberia-Newfoundland margin (Péron-Pinvidic et al., 2007), the rifting is relatively amagmatic with a broad ocean-continent transition that involves tectonically exhumed mantle. Passive seismological investigations provide fruitful avenues of inexpensive research to begin interrogation of the lithosphere of understudied regions such as the northern margin of the Gulf of Mexico. Here we report and discuss shear-wave splitting observations for the crust and upper mantle beneath the northern margin of the Gulf of Mexico.

The region that spans the northern Gulf of Mexico margin underwent two complete cycles of continental rifting (540 and 170 Ma) and collisional orogeny (ca. 1000 and 350 Ma) along the southern flank of Laurentia (e.g., Thomas, 2006). These events include the late Mesoproterozoic Grenville orogen, early Cambrian–middle Paleozoic continental rifting and passive margin formation, late Paleozoic Ouachita orogeny during the final stages of assembly of Pangea, and formation of the modern continental margin accompanied by brief seafloor spreading and oceanic crust formation during the Jurassic (ca. 165 Ma). The lithosphere that formed or was reworked during these tectonics events is preserved across a region that extends from the Grenville province of the craton to Jurassic oceanic crust in the Gulf of Mexico (Fig. 1). Over this broad transition, a very thick sedimentary succession has built upward and seaward (Harry and Londono, 2004). Thus, we know very little about the deep structure and boundaries within the craton–ocean-continent transition–oceanic

crust region, or even the location of the transition to oceanic crust for the intensely studied Gulf of Mexico (Bird et al., 2005).

Splitting of P-to-S converted waves (SKS) at the core-mantle boundary on the receiver side is a robust tool to examine finite strain caused by mantle deformation (for reviews see Silver, 1996; Savage, 1999). The polarization direction of the fast shear wave defines the orientation of the anisotropy, and the arrival time difference between the fast and slow waves (splitting time) measures the magnitude of mantle deformation. Observations of anisotropic textures in deformed mantle rocks and measurements of their seismic anisotropy reveal that lattice-preferred orientation of olivine crystallographic axes is the main cause of mantle anisotropy. Under uniaxial compression, the a-axis of olivine, along which seismic P waves travel fastest, aligns perpendicular to the maximum compressional strain direction; under pure shear, it becomes perpendicular to the shortening direction; and under progressive simple shear, it aligns in the flow direction (Ribe and Yu, 1991; Zhang and Karato, 1995). Vertical or subvertical magmatic dikes in the lithosphere can also produce significant shear-wave split-

ting with a fast direction along the strike of the dikes (Gao et al., 1997).

In spite of numerous observational and theoretical studies, the origin of mantle anisotropy is debated. Based on the observation that most fast directions parallel regional tectonic trends of surface geological features, several authors have proposed that at least locally, mantle anisotropy is caused by coherent deformation of the lithosphere (e.g., Silver and Chan, 1991; Liu et al., 1995; Silver, 1996; Silver et al., 2001). Another explanation is that mantle anisotropy is caused by active asthenospheric flow (Vinnik et al., 1992; Gao et al., 1994). This hypothesis is based on the observation that many observed fast directions parallel absolute plate motion, although significant differences are also documented. The asthenospheric flow hypothesis attributes such differences to small-scale or regionalized mantle flow, as suggested beneath areas such as the Tien Shan (Makeyeva et al., 1992), Baikal rift zone (Gao et al., 1994, 1997), Rio Grande rift (Sandvol et al., 1992), western United States (Savage and Sheehan, 2000), and northeast Asia above the deflected Pacific slab (Liu et al., 2008).

As demonstrated here, our measurements suggest that either mechanism can dominate, depending on the tectonic setting and the lithospheric structure and thickness.

## GEOLOGICAL SETTING OF THE STUDY AREA

We are particularly interested in what shear-wave splitting measurements can reveal regarding the transition from cratonic continental crust across transitional crust into oceanic crust. Here we examine shear-wave splitting for seven permanent broadband seismic stations in the south-central United States, in Texas, Oklahoma, and Arkansas.

Figure 1 shows the locations of these seismic stations and major tectonic provinces (Thomas, 2006) superimposed on a gravity map of the region (Sandwell and Smith, 1997). The Ouachita front approximates the boundary between the North American craton to the north and west from transitional crust to the east and south (e.g., Kruger and Keller, 1986; Keller et al., 1989). The craton is predominantly Mesoproterozoic granitic and metamorphic rocks (1.0–1.4 Ga) exposed locally and recovered from drilling (Barnes et al., 2002; Anthony, 2005; Goodge and Vervoort, 2006). The large gravity high extending to the northwest from near the Texas-Oklahoma border corresponds to a zone of ca. 540 Ma magmatism and rifting and ca. 300 Ma thrusting known as the southern Oklahoma aulacogen (Hoffman et al., 1974; Keller and Baldridge, 1995; Hogan and Gilbert, 1998). Station AMTX is near the western terminus of the main segment of the aulacogen and station WMOK is in the aulacogen. Station MIAR in southwest Arkansas is in a region dominated by ca. 300 Ma thrusting of the Ouachita orogenic belt. Station JCT is located ~50 km west of a large exposure of Mesoproterozoic crust (Llano uplift). We treat these four stations as "cratonic" for the purposes of this report. Station NATX is in the East Texas Basin, which formed by Jurassic rifting ca. 165 Ma. Stations HKT and KVTX are on transitional crust that also formed by Jurassic rifting. We group these three stations as sampling "transitional crust" for the purposes of this report.

## DATA AND METHOD

In the study area shown in Figure 1, data from a total of seven broadband seismic stations are available from the IRIS (Incorporated Research Institutions for Seismology) Data Management Center. The stations are sparsely distributed in the study area, with intervals of 200 km or greater. The amount of time during
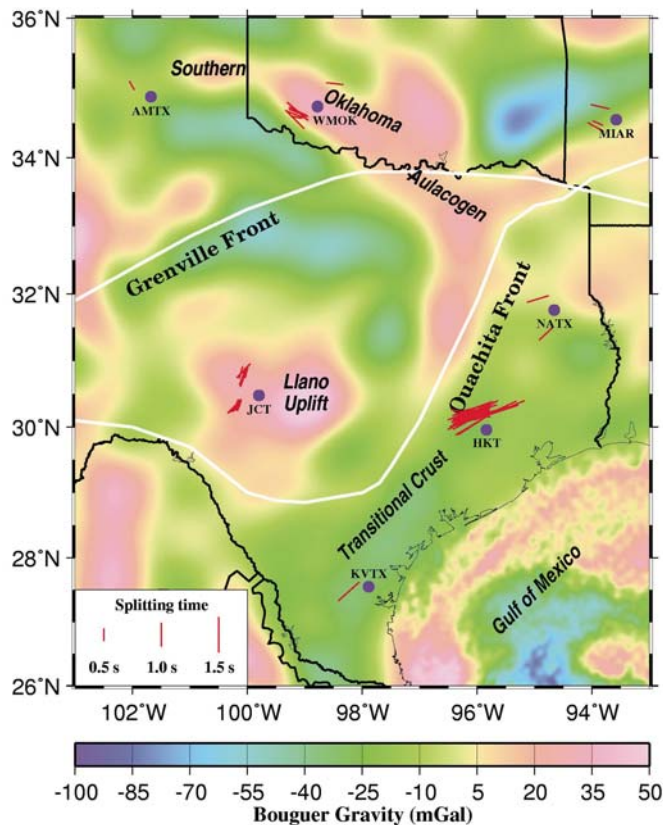


Figure 1. Gravity anomalies and shear-wave splitting measurements plotted above the SKS ray-piercing points at 200 km depth. Terrane boundaries are modified from Thomas (2006).

which data were recorded ranges from 7 months at NATX to ~12 yr at HKT and WMOK, with a mean of 6.7 yr.

We requested all the available broadband high-gain data from the IRIS Data Management Center recorded prior to May 2007, from earthquakes with an epicentral distance of 85°–140°. The cutoff body-wave magnitude is 5.6 for events shallower than 100 km, and 5.5 for deeper events. The seismograms were band-pass filtered in the 0.04–0.5 Hz range to enhance signal to noise ratio. The approach of Silver and Chan (1991) was used to search for the optimal fast direction and splitting time that correspond to the minimum SKS energy on the corrected transverse component. The F-test is used to estimate the 95% confidence interval of individual measurements (Silver and Chan, 1991). Averaged shear-wave splitting parameters for a station (Table 1) are computed using standard Gaussian statistics as weighted mean values of the splitting parameters from the individual events, and the standard deviations (STDs) of the mean values are the weighted STDs when the number of events is two or greater, and are taken as the STDs from the F-test for stations with only one event. We also computed weighted means of the fast directions using circular (von Mises) statistics (Mardia and Jupp,

TABLE 1. MEAN SKS SPLITTING MEASUREMENTS

| Station name | Coordinates | | Fast direction (°) | Splitting time (s) | Number of events |
|---|---|---|---|---|---|
| | Latitude (°N) | Longitude (°W) | | | |
| AMTX | 34.88 | 101.68 | 150 ± 8 | 0.4 ± 0.1 | 1 |
| HKT | 29.96 | 95.84 | 70 ± 5 | 1.6 ± 0.2 | 31 |
| JCT | 30.48 | 99.80 | 28 ± 11 | 0.4 ± 0.1 | 27 |
| KVTX | 27.55 | 97.89 | 48 ± 3 | 1.2 ± 0.1 | 1 |
| MIAR | 34.55 | 93.58 | 105 ± 9 | 0.6 ± 0.2 | 3 |
| NATX | 31.76 | 94.66 | 72 ± 18 | 0.9 ± 0.1 | 2 |
| WMOK | 34.74 | 98.78 | 116 ± 11 | 0.8 ± 0.2 | 7 |
| *Note:* The error represents one standard deviation. | | | | | |

2000; Audoine et al., 2004) and found that the results are virtually identical to those computed using Gaussian statistics.

## RESULTS

We made 72 well-defined measurements. Station averages are listed in Table 1 and shown in Figure 2. Relative to typical Global Seismographic Network (GSN) stations, the stations used in this study have high noise levels, most likely due to local site effects of the thick loose sediment layer beneath most of the stations. In addition, less rigorous installation standards relative to GSN stations (except for HKT, which

is a GSN station), high cultural activities, and waveform distortion associated with lithospheric structural complexity in the study area (Audoine et al., 2004) could all have contributed to the small number of high-quality measurements. Although stations AMTX and KVTX have only one measurement each, the results are reliable, as evidenced by the clear SKS signals, the similarity between the computed fast and slow components, and the linearity of the corrected particle motions (Fig. 3). Figure 1 shows the resulting splitting parameters plotted above the 200 km deep ray-piercing points. The mean splitting times range from 0.4 s at AMTX to as large as 1.6 s at HKT. The three stations that are
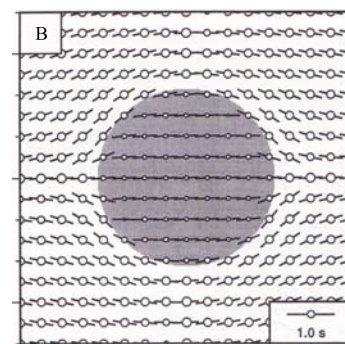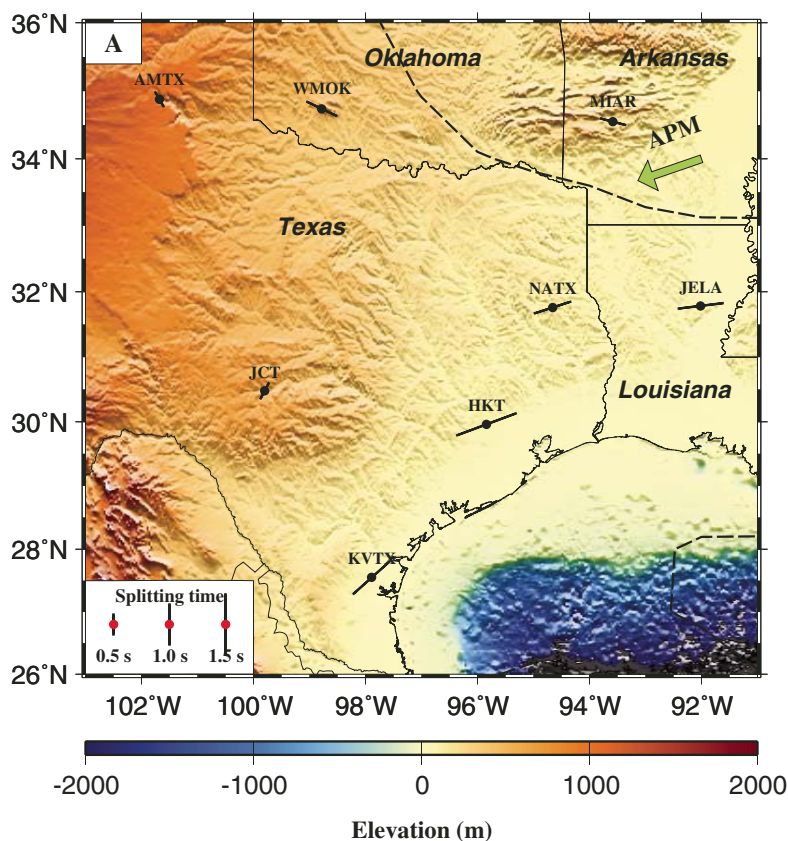




Figure 2. (A) Averaged shear-wave splitting parameters. Results at JELA are from Barruol et al. (1997). The arrow represents the absolute plate motion direction in a hotspot reference frame (Gripp and Gordon, 2002). Dashed line in the northeast corner of the study area is the 3% shear-wave velocity anomaly contour in the top 100 km, approximating the southwest boundary of the North American craton (Grand, 2002). (B) Predicted shear-wave splitting fast directions around a cratonic keel (Fouch et al., 2000).

probably located on transitional crust show the largest splitting times (0.9–1.6 s).

No previous splitting measurements were published for AMTX, JCT, KVTX, and NATX. Results from three of the stations (WMOK, MIAR, HKT) were previously obtained by other research groups, and most of them are in good agreement with our results. For HKT, Pulliam and Sen (1998) obtained a mean fast direction of 70° ± 4° and a splitting time of 1.55 ± 0.18 s, statistically consistent with our measurements. Barruol et al. (1997) reported a mean fast direction of 109° ± 4° and a splitting time of 0.77 ± 0.07 s at WMOK. For MIAR, using four events that occurred in 1992–1995, Barruol et al. (1997) found a mean fast direction of 89° ± 6° and a splitting time of 1.15 0 ± 0.14 s, which are statistically significantly different from our measurements (Table 1). Both our and the study of Barruol et al. (1997) used event 1995–235–07 and obtained almost identical results from the

former (104° ± 4°, 0.85 ± 0.15 s), and from the latter (105° ± 7°, 0.85 ± 0.2 s). The discrepancy in the averaged parameters for MIAR could be due to the fact that our study only uses events with excellent signal to noise level and therefore the results are better constrained.

## DISCUSSION

### Correspondence between Surface Geology and Splitting Measurements at Cratonic Stations

The fast directions observed at the four cratonic stations mostly parallel the strike of local geological features, suggesting that old structures within the lithosphere control the observed anisotropy, and that there is a high-degree of coherency between the deformation of the crust and the subcrustal lithosphere (Silver, 1996).

The parallelism between the strike of the southern Oklahoma aulacogen and the fast directions observed at stations WMOK and AMTX is similar to what is observed in active continental rift zones, such as the Baikal (Gao et al., 1997), Rio Grande (Sandvol et al., 1992), and East African rifts (Gao et al., 1997; Kendall et al., 2005) at stations near the rift axes. One of the mechanisms proposed for this parallelism is rift-parallel magmatic cracks or dikes in the lithosphere (Gao et al., 1997; Kendall et al., 2005). Rift-parallel vertical dikes may form a transverse isotropy with a rift-orthogonal axis of symmetry. The fast direction of the anisotropy would parallel the strike of the dikes, i.e., parallel to the rift axis. The effect of the dikes on SKS splitting is similar to that of fluid-filled cracks in the upper crust on splitting of shear waves from local earthquakes (Li et al., 1994). For active rifts, anisotropy is produced by the low shear-wave velocity of the dikes
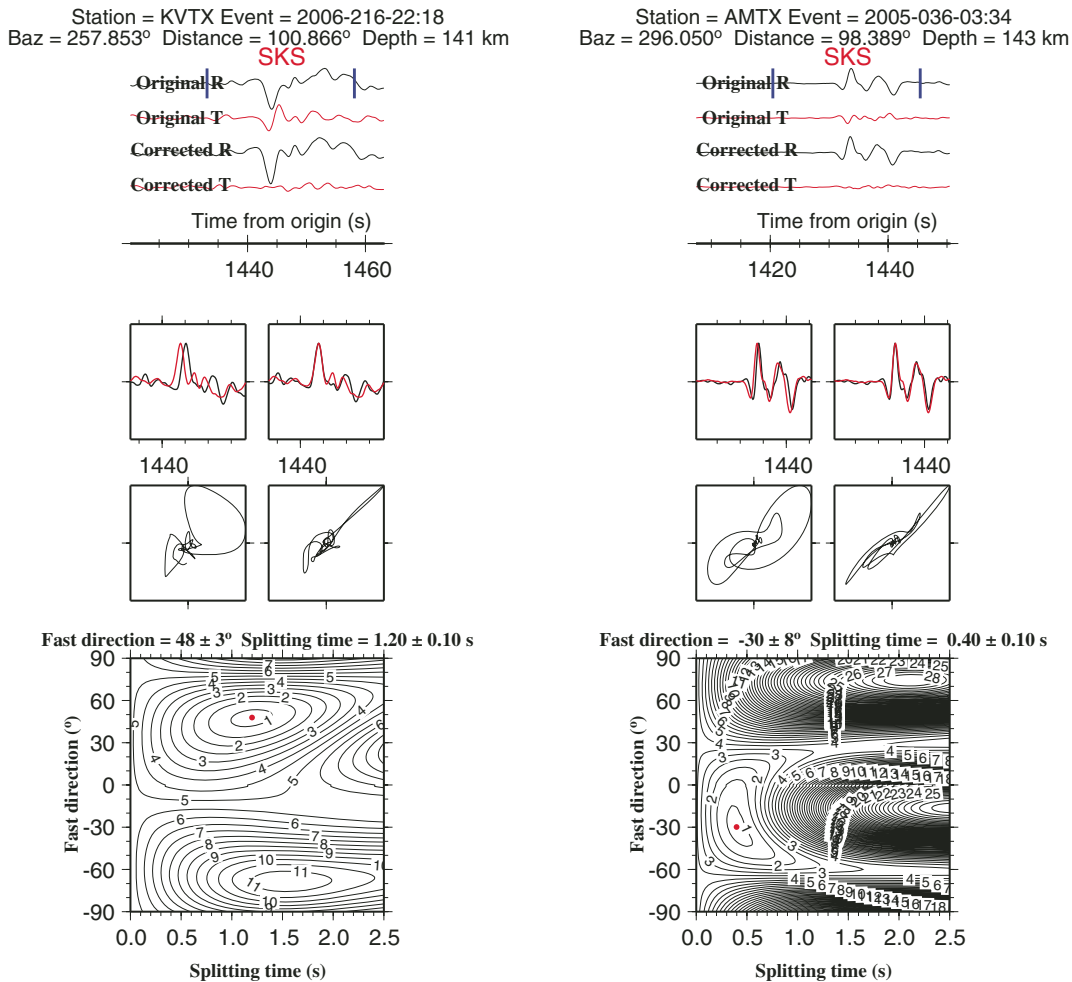


**Figure 3. Original and corrected radial and transverse SKS components and their particle motions for stations KVTX (left) and AMTX (right).**

relative to surrounding rocks, while for ancient rifts, a slightly high velocity is expected in the dikes and the magnitude of anisotropy is likely smaller than that beneath active rifts. Paleozoic rifting of the aulacogen parallels a group of ca. 1350 Ma northwest-striking dikes (Thomas, 2006*)* and massive synrift intrusions are required to explain the linear gravity high (Fig. 1) and the seismic velocity structure of the aulacogen (Keller and Baldridge, 1995). Surface geological observations and crustal-scale geophysical experiments suggest that the crust beneath the aulacogen is dominated by a large thick (~10 km) mafic layered complex, the Glen Mountains layered complex, overlain by thin A-type sheet granites and rhyolite cover (Hogan and Gilbert, 1998). Combined results from petrologic and gravity models indicate that the surface igneous rocks are underlain by an additional massive mafic igneous complex, similar to the anorthosite-mangerite-charnockite-granite complexes common to the Proterozoic, in the middle crust (Hogan and Gilbert, 1998).

The second possible cause for the formation of anisotropy with a rift-parallel fast direction is along-rift active asthenospheric flow (Sandvol et al., 1992). For the southern Oklahoma aulacogen, which is a failed rift, this model requires that the lattice-preferred orientation in the asthenosphere has survived the 540 m.y. since the rift became inactive and during the process when the asthenosphere was cooling to become lithosphere. Given these time constraints, we consider this possibility to be unlikely.

The third possible model of rift-parallel anisotropy is the rift-orthogonal compressional strain associated with the closing of the aulacogen ca. 350 Ma. Fast directions orthogonal to the maximum compressional strain have been observed in other fold-and-thrust belts, and are generally considered to reflect the lattice-preferred orientation of the olivine a-axis in the compressional strain field (Silver, 1996). If rift-orthogonal compressional strain is the cause of the observed anisotropy, the splitting time (0.8 s) observed at WMOK suggests coherent shortening of the crust and a significant portion of the subcrustal lithosphere as a result of a regional compressional stress field, perhaps associated with the Ouachita orogeny.

The smaller splitting time observed at AMTX, which is located at the western terminus of the aulacogen and thus is in a region where the compressive deformation is modest and the magmatism was reduced, can be explained by a lower volumetric composition of magmatic cracks, weaker rift-parallel flow, or smaller rift-orthogonal compressional strain.

At station MIAR (on the Benton uplift of the Paleozoic Ouachita orogenic belt; e.g., Keller et al., 1989), the fast direction is ~45° from the regional strike of the orogenic belt. In spite of the large angle between the observed fast direction and the surface expression of the orogenic belt, we argue that lithospheric structures contribute significantly to the observed anisotropy, because (1) the integrated geophysical model of Kruger and Keller (1986) and Mickus and Keller (1992) show that the Benton uplift is an allochthonous feature that overlies the edge of the craton, and therefore the strike of the orogeny observed on the surface does not necessarily represent the regional trend of the orogeny and lithospheric deformation at depth; (2) the nearby lithosphere of the craton such as that beneath eastern Missouri and central Illinois shows dominantly northeast fast directions (Fouch et al., 2000;) that are parallel to the absolute plate motion direction of the North American continent and are significantly different from the fast direction observed at MIAR; (3) on a larger scale, the fast direction at MIAR is consistent with the strike of the Ouachita orogen in eastern Arkansas and northern Mississippi. The splitting time of 0.6 s implies an ~90 km layer with 3% anisotropy. If this layer is in the upper lithosphere and the anisotropy formed by north-south compression associated with the Ouachita orogeny, the shear-wave splitting measurements suggest significant lithospheric shortening (Zhang and Karato, 1995). However, geology and crustal structure studies suggest that the Ouachita orogeny did not involve significant crustal shortening in this location (Keller et al., 1989; Thomas, 2006), implying possible decoupling between the crust and the mantle portion of the lithosphere beneath the Benton uplift. This is consistent with the suggestion that the uplift is an allochthonous feature (Mickus and Keller, 1992).

Station JCT is located west of the Llano uplift. Positive gravity anomalies and deep drilling data suggest that rocks beneath the station are similar to those of the uplift (Fig. 1). These rocks formed during the 1350–1000 Ma Grenville orogeny (Carlson, 1998; Mosher, 1993). Relative to the global average splitting time of ~1 s for continental stations, the value of 0.4 ± 0.1 s observed at JCT is small. This could reflect relaxation of mantle fabrics during the 1000–1100 Ma thermal event (Walker, 1992) or canceling of the splitting time by two (or more) anisotropic layers with nearly orthogonal fast directions. The existence of multiple layers with differently fast directions beneath JCT is suggested by the azimuthal variation of fast directions (Silver and Savage, 1994), with events from the northwest showing nearly north-south fast directions and events from the southwest showing mostly northeast-southwest fast direc-

tions (Fig. 1). However, the limited azimuthal coverage prevents a unique solution to the splitting parameters of each layer.

## Possible Causes of Anisotropy at Transitional Crust Stations

Fast polarization directions at the transitional crust stations are approximately parallel to the continental margin. The splitting times at the three stations range from 0.9 to 1.6 s; these are the largest in the study area and require a 130–240-km-thick layer with 3% anisotropy. It is interesting that Barruol et al. (1997) reported that the fast direction at an analog station located in central Louisiana (JELA, Fig. 2) has splitting time of 1.1 s and a fast direction of 83°, which is parallel to the local strike of the continental margin.

Similar to the rift-parallel fast direction observed at WMOK, the anisotropy observed on the transitional crust could be related to vertical mafic dikes in the crust and mantle lithosphere. These are likely to parallel to the continental margin and to have formed during the opening of the gulf. Assuming that the lithosphere beneath the transitional area is 70 km thick, as suggested by seismic tomographic images (e.g., van der Lee and Frederiksen, 2005), the magnitude of azimuthal anisotropy must be 5.5%–10% in order to produce the 0.9–1.6 s splitting time. Less anisotropy is required for thicker lithosphere. Figure 4A shows this cause for strong anisotropy measured for transitional crust stations. Alternatively, strong, margin-parallel shear-wave splitting can result from preferred orientation of olivine crystals in the lithospheric mantle (Fig. 4B). Such rift-parallel flow may result from the preservation of asthenospheric fabrics as a result of lithosphere thickening due to conductive cooling of the asthenosphere. A large degree of anisotropy in the thin lithosphere is needed in order to produce the large splitting times.

The third model is that the present-day asthenospheric flow around the keel of the North America craton is mostly responsible for the observed anisotropy, as shown in Figure 4C. The observed fast directions at the ocean-continent transition stations are consistent with the predictions under a simple asthenospheric flow model (Fig. 2). This explanation is also consistent with the result of a recent joint inversion of surface waveforms and shear-wave splitting measurements, which reveals a two-layer anisotropy model for stable North America, the top layering being in the lithosphere and reflecting past tectonic deformation, and the lower layer being in the asthenosphere with fast directions parallel to the absolute plate motion direction (Marone
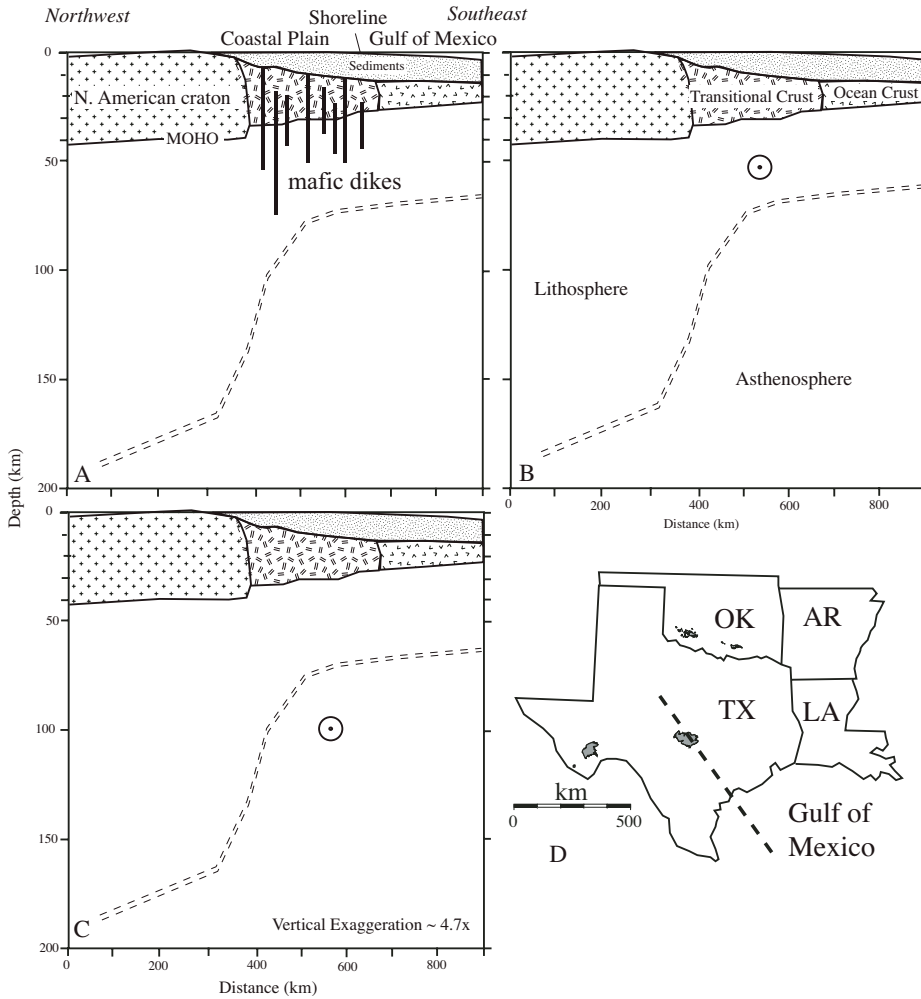
**Figure 4. (A–C) Schematic lithospheric sections across the Texas passive margin, from craton to oceanic crust, showing three possible explanations for margin-parallel shear-wave anisotropy, as described in text. Crustal structure is from Mickus et al. (2007). True locations of craton-transitional crust and transitional-oceanic crust boundaries and width and thickness of transitional crust are approximate. Double-dashed lines indicate possible location of asthenosphere-lithosphere boundary (van der Lee and Frederiksen, 2005). Circle with dot shows orientation of the a-axis of olivine (and asthenospheric flow lines in C), and location in the upper mantle where this anisotropy is concentrated. See text for further discussion. (D) Location of transect shown in A–C. Dashed line shows location of transect; gray areas are exposures of Precambrian basement.**

cracks or fossil flow, or a combination of these factors, is the most likely cause.

The interpretation of the results and the nature of the continental-oceanic lithosphere transition will remain vague until more detailed geological-geophysical studies are conducted. The transportable array stations of EarthScope's USArray, which will be installed in the study area during 2009–2010 with a station interval of ~70 km, will provide unprecedented data to address some of the remaining questions related to the accretion, structure, and modification of continental lithosphere. As advocated by Stern and Klemperer (2008), because of the large station spacing of the transportable array (~70 km), some of the fundamental issues can only be addressed by higher resolution studies using facilities such as the EarthScope flexible array and ocean bottom seismometers.

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**CONCLUSIONS**

The results presented herein demonstrate significant spatial variations and at the same time

consistency of shear-wave splitting with local geology in both the fast directions and splitting times. The measurements suggest that beneath areas with different tectonic histories, different mechanisms are responsible for generating seismic anisotropy. Beneath the "cratonic" stations in the study area, the correspondence between the observed shear-wave splitting parameters with local geologic features suggests that lithospheric deformation is mostly responsible for the observed anisotropy; beneath the transitional crust stations, asthenospheric flow beneath the thinned lithosphere, rift-parallel magmatic

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