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Kev Points:

- We evaluate SKS splitting at Transportable Array stations in eastern North America
- Evidence for contributions from both the lithosphere and the asthenospheric upper mantle
- Distinct signature of lithospheric deformation associated with Appalachian orogenesis

Supporting Information:

- Supporting Information S1
- Table S1
- Table S2
- Table S3

Correspondence to:

M. D. Long, maureen.long@yale.edu

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SKS splitting beneath Transportable Array stations in eastern North America and the signature of past lithospheric deformation

Maureen D. Long¹, Kenneth G. Jackson², and John F. McNamara²

¹Department of Geology and Geophysics, Yale University, New Haven, Connecticut, USA, ²Yale College, Yale University, New Haven, Connecticut, USA

Abstract Seismic anisotropy in the upper mantle beneath continental interiors is generally complicated, with contributions from both the lithosphere and the asthenosphere. Previous studies of SKS splitting beneath the eastern United States have yielded evidence for complex and laterally variable anisotropy, but until the recent arrival of the USArray Transportable Array (TA) the station coverage has been sparse. Here we present SKS splitting measurements at TA stations in eastern North America and compare the measured fast directions with indicators such as absolute plate motion, surface geology, and magnetic lineations. We find few correlations between fast directions and absolute plate motion, except in the northeastern U.S. and southern Canada, where some stations exhibit variations in apparent splitting with backazimuth that would suggest multiple layers of anisotropy. A region of the southeastern U.S. is dominated by null SKS arrivals over a range of backazimuths, consistent with previous work. We document a pattern of fast directions parallel to the Appalachian mountain chain, suggesting a contribution from lithospheric deformation associated with Appalachian orogenesis. Overall, our measurements suggest that upper mantle anisotropy beneath the eastern United States is complex, with likely contributions from both asthenospheric and lithospheric anisotropy in many regions.

1. Introduction

Eastern North America has a complex tectonic and geologic history that encompasses two complete Wilson cycles of supercontinent assembly and breakup over the past ~1.3 Ga [e.g., Hoffman, 1991; Thomas, 2006; Cawood and Buchan, 2007; Hatcher, 2010]. The assembly of the supercontinent Rodinia, complete by \sim 1 Ga, was accompanied by the Grenville orogeny, which deformed the eastern continental U.S. as far west as present-day western Ohio and central Tennessee (Figure 1). Subsequent continental breakup opened the lapetus Ocean, whose later closure associated with the Taconic, Acadian, and Alleghanian orogenies formed the Pangaea supercontinent between ~440-300 Ma and built the Appalachian-Ouachita orogenic belt. Rifting along the east coast of the present-day U.S. and Canada at \sim 200 Ma, roughly contemporaneous with the eruption of the Central Atlantic Magmatic Province (CAMP) basalts [e.g., McHone, 2000], began the opening of the Atlantic Ocean and the evolution of what is today a passive continental margin.

While this general outline of the geologic and tectonic history of the eastern U.S. is well known, there are several fundamental outstanding questions regarding the structure and dynamics of its underlying upper mantle. These include the extent and style of deformation of the continental lithosphere during past episodes of orogenesis and rifting, the postrift evolution of passive continental margin structure, controls on the temporal evolution and persistence of Appalachian topography, and the geometry of present-day upper mantle flow beneath the passive margin and its possible links to the remnant Farallon slab in the deep mantle and dynamic topography at the surface. Progress on many of these unsolved problems hinges on an understanding of both past and present deformation of the upper mantle beneath eastern North America. An important tool to study upper mantle deformation is the delineation and characterization of seismic anisotropy [e.g., Long and Becker, 2010], which in the upper mantle generally results from the lattice preferred orientation (LPO) of individual mineral grains in deformed rocks [e.g., Karato et al., 2008].

While the measurement of seismic anisotropy is a powerful tool for studying the deformation of the mantle, its interpretation in continental interiors is not straightforward [e.g., Silver, 1996; Fouch and Rondenay, 2006].

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Figure 1. (a) Map of stations used in this study (red triangles). Lines indicate the approximate positions of the Grenville deformation front (blue line) [*Whitmeyer and Karlstrom*, 2007], the New York-Alabama magnetic lineament (orange line) [*Steltenpohl et al.*, 2010], the Brunswick magnetic anomaly (yellow line) [*Parker*, 2014], and the Carolinia magnetic lineament (magenta line) [*Hatcher*, 2010]. (b) Map of events used in this study (red circles). All events that yielded at least one *SKS* measurements (null or nonnull) are shown.

In general, in continental regions there is a likely contribution from seismic anisotropy both in the lithospheric mantle, which reflects past deformational processes [e.g., *Tommasi and Vauchez*, 2015], and from the asthenospheric mantle, which reflects present-day deformation induced by the motion of the overlying plate, buoyancy-driven flow in the mantle, or a combination of these [e.g., *Fouch et al.*, 2000; *Forte et al.*, 2010]. From an observational perspective, there is abundant evidence for multiple layers of anisotropy beneath portions of North America, as inferred from surface wave models [e.g., *Deschamps et al.*, 2008], *SKS* splitting observations [e.g., *Levin et al.*, 1999], receiver function analysis [e.g., *Wirth and Long*, 2014], and combinations of these techniques [e.g., *Yuan and Romanowicz*, 2010; *Yuan and Levin*, 2014].

Measurements of the splitting or birefringence of *SKS* phases, which are converted from a *P* wave to an *S* wave at the core-mantle boundary, are a popular tool for studying azimuthal seismic anisotropy in the upper mantle [e.g., *Long and Silver*, 2009]. Previous studies of *SKS* splitting in the eastern U.S. have revealed evidence for a number of possible processes that may contribute to the observed anisotropy [e.g., *Barruol et al.*, 1997; *Levin et al.*, 1999; *Fouch et al.*, 2000; *Long et al.*, 2010; *Wagner et al.*, 2012], but interpretations have been hampered by the relatively sparse station coverage. This situation has changed dramatically in the past few years, with the arrival of the seismic Transportable Array (TA) component of EarthScope's USArray in the eastern U.S. and Canada [*USArray Transportable Array*, 2003]. TA stations have a nominal station spacing of ~75 km, drastically improving the spatial resolution of deep structures. Because the *SKS* splitting analysis technique has excellent lateral resolution (although its depth resolution is poor), the use of data from the TA provides the opportunity to address questions left outstanding by previous studies of *SKS* splitting in eastern North America.

Here we present a set of ~3900 high-quality measurements of *SKS* arrivals at ~380 TA stations in eastern North America (Figure 1), recorded through August 2014. Our focus in this paper is on the investigation of geographic patterns in measured splitting parameters (fast direction, ϕ , and delay time, δt) and comparisons with geologic and tectonic indicators such as topography, absolute plate motion (APM), and magnetic anomalies, with the goal of discerning the likely relative contributions of asthenospheric and lithospheric anisotropy. The data set presented here is complementary in its geographic coverage to other recent studies of *SKS* splitting beneath TA stations [e.g., *Liu et al.*, 2014; *Refayee et al.*, 2014; *Yang et al.*, 2014; *Hongsresawat et al.*, 2015]. As with previous studies, we find evidence that both asthenospheric and lithospheric anisotropy contribute to *SKS* splitting in eastern North America.

2. Data and Methods

We used data from TA stations in the eastern U.S. and southern Canada, extending as far south as ~31°N and as far north as ~47°N. In the northern half of the study region, we examined stations as far west as ~85°W, while the southern half of the study area extended to ~81°W. We examined data recorded through August 2014; given the timing of TA station deployment, most stations in the southern portion had up to ~24 months of data, while some stations in the northern portion had as few as ~10 months. Our data processing and shear wave splitting measurement procedures closely followed our previous work in the eastern U.S. [Long et al., 2010; Wagner et al., 2012], so the results can be compared directly. We selected *SKS* phases from earthquakes of magnitude 5.8 or greater at epicentral distances between 88° and 130° for analysis (Figure 1b). Data were bandpass filtered to retain energy at periods between 8 and 50 s; in a small minority of cases, corner frequencies were adjusted manually to optimize waveform clarity and signal-to-noise ratio, as in previous work [Long et al., 2010]. Given the characteristic periods of the *SKS* phases under study (~10 s), our analysis cannot resolve splitting with delay times less than ~0.5 s [e.g., Long and Silver, 2009].

Seismograms with clear SKS arrivals with initial polarizations (estimated from the waveforms) that were within 10° of the backazimuth were selected for analysis. We carried out shear wave splitting analysis using the SplitLab software [Wüstefeld et al., 2008], applying the rotation-correlation and transverse component minimization methods simultaneously. We only retained measurements for which the two measurement methods agreed, given the 95% confidence regions. We manually selected measurement windows, evaluated the linearity of corrected particle motion, and assigned quality rankings for each measurement. Measurements were ranked as "good," "fair," or "poor," with "good" measurements having 95% confidence regions of up to roughly \pm 20° in ϕ and \pm 0.5 s in δt and "fair" measurements up to roughly \pm 30° in ϕ and \pm 1.0 s in δt . Measurements ranked as "poor" had even higher levels of uncertainty associated with the splitting parameter estimates, but still demonstrated agreement between the two methods. We classified as null those SKS arrivals that had good signal-to-noise ratio and linear or very nearly linear uncorrected particle motion, with a "good" or "fair" rating assigned based on the degree of linearity and the noise level in the transverse component seismogram. We did not classify as "null" those SKS arrivals that exhibited transverse component energy but poorly constrained splitting; rather, we restricted our "null" classification to arrivals with (nearly) linear particle motion and high signal-to-noise ratio on both the radial and transverse components.

3. Results

Our data processing and measurement procedure resulted in measurements for 3902 individual *SKS* arrivals at TA stations in the eastern U.S. Of these, a large majority (85%) were null (that is, nonsplit) arrivals, meaning that the *SKS* phases had linear uncorrected particle motions and showed no sign of splitting. The large percentage of null arrivals measured at eastern U.S. stations points to the importance of characterizing and interpreting nonsplit *SKS* arrivals in this region. Maps of individual "good" and "fair" split measurements are shown in Figure 2, and maps of individual null measurements are shown in Figure 3. We report "poor" measurements in our data tables and include them in histograms of the distribution of results, but do not include them in our single-station averaging procedure. Of the nonnull splitting measurements reported in this study, a small minority (~9%) was ranked "poor." Individual measurements, along with their associated errors and quality rankings, can be found in supporting information Tables S1 and S2.

Inspection of the individual measurement maps in Figures 2 and 3, and the associated histograms of the distribution of the measurements, reveals several general features of the data set. Measured fast directions (Figure 2) generally trend NE-SW in the southern two-thirds of our study area, while the overall trend is closer to E-W in the northern portion. A histogram of measured ϕ values for the entire data set (Figure 2c) shows a clear, unimodal distribution around an average value of 70°. A histogram of measured δt values (Figure 2d) is similarly distributed about an average value of 1.1 s, close to the generally accepted average value of 1.0 s for continental regions [e.g., *Silver*, 1996; *Fouch and Rondenay*, 2006] but smaller than typical measured *SKS* delay times for the western U.S. [e.g., *Hongsresawat et al.*, 2015]. The backazimuthal distribution of null *SKS* arrivals in the eastern U.S. is more scattered than the measured fast directions (Figure 3a), but a histogram (Figure 3b) reveals two clear peaks near the average measured ϕ value of 70° and a direction 90° from this average; the latter would correspond to the average slow direction. For the simple case of



Figure 2. (a) Map of individual splitting measurements of "good" or "fair" quality. Measurements are plotted at station location with a bar whose orientation is aligned with the fast direction and length is scaled to the delay time (scale bar at bottom right indicates 1 s delay time). Stations at which we measured at least five null *SKS* arrivals, with no high-quality split arrivals, are shown with white circles; other stations are shown with red circles. (b) Histogram of measured fast directions (modulo 180°) for all measurements in the data set. The average fast direction is shown with a dashed purple line. (c) Histogram of measured delay times for all measurements in the data set. The average delay time is shown with a dashed black line.

a single anisotropic layer, *SKS* phases that have initial polarizations equivalent to either the fast or slow direction of the medium are not split [e.g., *Long and Silver*, 2009, and references therein].

In order to facilitate the interpretation of the data set and comparison of the measured fast directions with geologic indicators, we calculated average splitting parameters (ϕ , δt) at each station, as shown in Figure 4a and supporting information Table S3. This calculation is based on the highest-quality split measurements at each station: for each station, we calculated average values of the "good" and "fair" quality measurements. For comparison, we also computed single-station average values with "poor" measurements included; these values are generally very similar, but we chose to present the averages based only on the higher-quality measurements in this paper. We identified a large number of stations that exhibited only null arrivals and for which we did not measure any split *SKS* arrivals; such stations with at least 5 high-quality null measurements are also shown on the map in Figure 4a (white dots). While the use of single-station averages obscures potential complexities in anisotropic structure, it allows us to evaluate the first-order characteristics of the splitting data set and identify geographic trends.

While there is very little geographic overlap between this study and previously published studies of *SKS* splitting at TA stations, we can compare the averages in Figure 4a with results obtained by *Hongsresawat et al.* [2015] just to the west of our study area. Additionally, for a small number of stations in Alabama we can compare our results to theirs directly. Despite the difference in preprocessing procedures and measurement method between the two studies, we obtain single-station average fast directions that are strikingly



Figure 3. (a) Map of individual null measurements of "good" or "fair" quality. Null arrivals are indicated with a line that points in the direction of the station to event azimuth (backazimuth). Stations at which we measured at least five null *SKS* arrivals, with no high-quality split arrivals, are shown with white circles; other stations are shown with red circles. (b) Histogram of the distribution of backazimuths (modulo 180°) for null arrivals for the entire data set. Dashed black lines indicate the average fast direction for the entire data set (pink dashed line in Figure 2b) and a direction 90° from the average fast direction, and correspond roughly to peaks in the histogram.

similar to theirs in adjacent or overlapping regions, particularly at stations in western Alabama that are common to both studies.

A number of notable geographic patterns in both the null and nonnull fast direction measurements emerge in the single-station average maps (Figure 4a). To aid interpretation, we have divided the maps into five regions (A-E) based on the distinctive splitting behavior within that region, as shown in Figures 4b and 4c. Boundaries between the regions were estimated qualitatively; the designations of the different regions are not meant to be hard and fast, but rather general guides to our first-order interpretation. Region A encompasses the northern portion of our study area, roughly north of 42°N in the western part but extending as far south as Maryland and Delaware in the region east of the Appalachian Mountains. In this region, we observe fast directions that trend roughly E-W, with an average fast direction (77°) that is rotated slightly clockwise from that of the overall data set (70°). Within region A, there are smooth lateral variations in average ϕ ; for example, in Maine stations exhibit fast directions that are generally E-W, while the region of Ontario to the west of Michigan's Upper Peninsula exhibits fast directions that are generally NE-SW. We also observe a number of stations, particularly in southern New York and southern New England, that have a limited number of observations and for which we cannot determine an average splitting pattern, likely due to short run times of the stations, generally weak splitting, higher levels of cultural noise, or a combination of these factors.

We also identify a set of stations, designated as Region B, that delineate a swath of the Appalachian Mountains from northeastern Alabama through central Pennsylvania and exhibit fast directions (average $\phi = 61^{\circ}$) that are generally parallel to the strike of Appalachian topography. Average delay times in this region are 1.0 s, very close to the average for all of eastern North America. To the east of Region B, we identify a large group of stations in Virginia, North Carolina, northern South Carolina, and northern Georgia that we have designated as Region C. In this region, we identify a large number of stations that are dominated by null arrivals, many with at least five null measurements (white dots in Figure 4a), with a much smaller number of stations that exhibit splitting. For this group of stations, out of 552 total measurements, only 25 (less than 5%) correspond to split waveforms, while the remaining 527 correspond to nonsplit waveforms with clear



Figure 4. (a) Map of single-station average splitting parameters. For each station, we have taken a simple (nonweighted) circular average of fast direction, and a simple average of delay time, for all "good" and "fair" measurements. Plotting conventions for fast direction and delay time are as in Figure 2a. (b) Map showing our division of the study area into five regions (Regions A-E) based on splitting behavior. (c) Same as Figure 4a, but here we overlay the boundaries of Regions A-E from Figure 4b (gray lines) as well as lines showing major magnetic lineaments (as in Figure 2a). (d) Map of single-station average splitting parameters (as in panel a) plotted on top of the magnetic anomaly data of *Maus et al.* [2007], with positive anomalies shown in red and negative anomalies in blue. Magnetic anomaly values range between roughly ±150 nT. For clarity, only stations that exhibit splitting are shown (yellow dots).

linear particle motion. Of the split arrivals in region C, the average delay times are slightly smaller (0.9 s) than the average δt for the entire data set.

In the southernmost portion of our study region, corresponding to the southern parts of Alabama, Georgia, and South Carolina, we identify a region with relatively strong and coherent splitting that we designate as Region D. Similar to the rest of eastern North America, in this region there is a high proportion of null

arrivals (255 out of 304, or 84%), but most stations in this region also exhibit splitting with an average delay time of 1.2 s, slightly higher than the overall average. There is a notable rotation of ϕ within this region from nearly E-W in southern Alabama to generally NE-SW in southeastern Georgia and South Carolina. Although most stations in Region D exhibit splitting, these stations are interspersed with stations that exhibit only null arrivals. Finally, we designate as Region E the portion of the study area to the west of Region B in the Appalachian Mountains. In this region, there is a mix of stations that exhibit clear splitting and those that exhibit only null arrivals, and we document generally smooth lateral variations in average ϕ for those stations that exhibit splitting. In central and eastern Kentucky, average fast directions trend NNE-SSW, while in southeastern Indiana and Ohio there is a mix of NE-SW and E-W trending ϕ values.

4. Discussion

A key challenge in the interpretation of *SKS* splitting measurements in continental settings is the lack of depth resolution; because *SKS* phases have nearly vertical paths in the upper mantle, their depth resolution is poor, although lateral resolution is excellent [e.g., *Long and Silver*, 2009]. There is ample evidence from previous work that the anisotropic structure of the upper mantle beneath continental North America is layered, with likely contributions from both present-day flow in the asthenosphere and frozen-in structure in the lithospheric mantle [e.g., *Levin et al.*, 1999; *Deschamps et al.*, 2008; *Yuan and Romanowicz*, 2010; *Wagner et al.*, 2012; *Wirth and Long*, 2014; *Yuan and Levin*, 2014; *Hongsresawat et al.*, 2015]. An additional potential factor is the possibility of a contribution to *SKS* splitting from anisotropy in the lowermost mantle, which is not generally considered to be a first-order effect but which has been documented in some regions [e.g., *Niu and Perez*, 2004; *Long*, 2009; *Lynner and Long*, 2012]. Because our interpretation focuses on the single-station average splitting maps that include data over a range of backazimuths, it is unlikely that lowermost mantle anisotropy makes a major contribution to our data set. It is worth noting, however, that the potential contribution to *SKS* splitting from lowermost mantle anisotropy beneath North America, which has been documented using *ScS* phases [e.g., *Nowacki et al.*, 2010], has not yet been evaluated in detail.

It is likely that there are contributions to our eastern North America splitting data set from both the asthenosphere and the lithosphere. Because of the limited depth resolution, it is difficult to quantitatively evaluate the relative contributions at each station, but one common strategy is to compare measured fast directions to attributes such as absolute plate motion (APM) and the local orientation of geologic indicators such as topographic features or magnetic anomalies (shown in Figure 4d), which likely indicate basement crustal structures [e.g., *Wüstefeld et al.*, 2010; *Wagner et al.*, 2012]. For each of the five regions discussed in section 3 above, we have computed histograms (Figure 5) of the distribution of fast directions or incoming polarization angles for null arrivals, as appropriate, for comparisons with APM and geologic indicators in each region.

Because the calculation of APM depends on the plate motion model and reference frame, we show several different estimates of APM on each plot, including those obtained using the HS3-Nuvel1A plate motion model [*Gripp and Gordon*, 2002] in both a hotspot reference frame (HS3) and in a no-net-rotation (NNR) frame. We also use a reference frame recently proposed by *Becker et al.* [2015], hereinafter B15, that is based on the MORVEL56 model [*Argus et al.*, 2011] but includes a net rotation of the lithosphere such that motions are aligned with seafloor spreading directions and provide a generally good global fit to azimuthal anisotropy in the upper mantle. In this paper we focus on comparisons with APM, which is useful for evaluating a model in which asthenospheric flow is dominated by horizontal shearing due to plate motion, in combination with A-, C-, or E-type olivine fabric [*Karato et al.*, 2008]. However, there is likely also a component of density-driven flow in the upper mantle [e.g., *Forte et al.*, 2010; *Conrad and Behn*, 2010; *Becker et al.*, 2014]. The relative contributions of buoyancy-driven flow and APM-parallel shear in the upper mantle beneath continents are not well understood, but future testing of the predictions of mantle flow models beneath eastern North America against anisotropy observations will be essential.

The distribution of fast directions within each region and comparisons with APM shown in Figure 5 strongly suggest that there is some contribution from lithospheric anisotropy in most regions of eastern North America. That is, the observations are not entirely matched by a model that invokes horizontal shearing in the asthenospheric upper mantle due to APM as the sole cause of upper mantle anisotropy. Within Region A (Figure 5a), there is a fairly wide range of observed ϕ values, and while it is true that the average



Figure 5. (a) Histogram of individual fast direction measurements for Region A. The measured average ϕ value for the region is shown with a dashed purple line. Dashed red line indicates the average value in the region for APM (modulo 180°) for the plate motion model of *Gripp and Gordon* [2002] in a Pacific hotspot reference frame. Dashed green line indicates average value for APM (modulo 180°) for the same plate motion model in a no-net-rotation reference frame. Dashed yellow line indicates the average value for APM (modulo 180°) for the same plate motion model in a no-net-rotation reference frame. Dashed yellow line indicates the average value for APM (modulo 180°) in the reference frame of *Becker et al.* [2015]. (b) Same as Figure 5a, but for Region B. (c) Histogram of backazimuths for null *SKS* arrivals for Region C. (d) Same as Figure 5a, but for Region D. (e) Same as Figure 5a, but for Region E.



Figure 6. Examples of single-station splitting patterns for three stations located in Region A (from left to right, stations E51A and E52A in southern Ontario, and station H65A in central Maine). Measurements are plotted as a function of backazimuth (angle from the top of the circle) and incidence angle (distance from center). Null arrivals are indicated with red circles; nonnull arrivals are plotted with green ("good" quality measurements) or blue ("fair" quality measurements) bars whose orientation and length correspond to the fast direction and delay time, respectively. Stations E51A and E52A show some evidence for complexity in their splitting patterns, with apparent splitting parameters that vary with backazimuth and a complicated distribution of null arrivals. In contrast, station H65A exhibits relatively simple splitting.

measured ϕ value of 77° is very close to the APM for the B15 reference frame, it is also clear from both the histogram and the map view in Figure 4a that there are significant regional deviations from this value (e.g., in northern Maine and southern Quebec). The APM value for the NNR reference frame does not match the observations well in general, while the APM in the HS3 reference frame is within ~10° of that of B15.

We suggest that within Region A of our study area, there is likely a contribution to *SKS* splitting from plate motion parallel shearing of the asthenospheric mantle, but there is also a contribution from the lithosphere that varies laterally and/or vertically, causing the spatial variations visible in the map in Figures 4a and 4c. There is some tentative support for this hypothesis found in single-station splitting patterns at stations in Region A; in Figure 6, we show example stereoplots that exhibit measured *SKS* splitting parameters that vary with backazimuth for selected stations in this region. For many of the stations in Region A, only 10 months of data were available at the time of our analysis, so our view of possibly complex single-station splitting patterns is incomplete. In particular, we are unable to distinguish between systematic variations with backazimuth that might suggest multiple layers of anisotropy (or dipping axes of symmetry) and variations that are not systematic and might suggest small-scale heterogeneity or inconsistent measurements. Nevertheless, some of the steroplots in Figure 6 hint at backazimuthal variations in apparent splitting parameters, which would suggest complex anisotropy that varies laterally and/or with depth. However, a comparison between measured fast directions in Region A and magnetic anomalies [*Maus et al.*, 2007] (Figure 4d), which might correspond to deep crustal structures, reveal few obvious correlations.

One of the more striking features of our *SKS* data set for eastern North America is the observation of fast directions parallel to the strike of the Appalachian mountain chain beneath stations in or near the regions of highest present-day Appalachian topography, stretching through northeastern Alabama to Pennsylvania (Region B). The trend in ϕ appears to generally follow the strike of the mountain range, including a pronounced rotation to nearly E-W fast directions in central Pennsylvania. This rotation in ϕ is coincident with a bend in the topography known as the Pennsylvania Salient, which may reflect orogenic bending around rigid lower crustal material associated with magmatic rifting during the Proterozoic [*Benoit et al.*, 2014]. The fast directions in Region B are also generally parallel to the strike of the New York-Alabama magnetic lineament (Figures 1 and 4c), although the lineament does not exhibit the same bend in Pennsylvania that is evident in the topography. This lineament is an enigmatic structure that may correspond to a crustal-scale strike-slip fault at the eastern edge of the Appalachian Plateau [*Steltenpohl et al.*, 2010]. Our observation of lineament-parallel ϕ is consistent with previous observations at permanent stations in this region [*Long et al.*, 2010; *Wagner et al.*, 2012]. The coherent splitting within Region B contrasts with the behavior we observe at stations to the east in Region C, which is dominated by null *SKS* arrivals. Of particular note is a "band" of stations within region B through Tennessee, North Carolina, Kentucky, and Virginia that exhibit

coherent and relatively strong splitting and are surrounded to the east and west with stations that show null splitting, arguing for a distinct lithospheric anisotropy signature beneath Region B.

At first glance, the coincidence between the measured fast directions and geologic indicators such as the New York-Alabama lineament and the strike of Appalachian topography, along with the stark contrast in splitting behavior with surrounding stations, would argue for a primary contribution from lithospheric anisotropy from past deformation processes in this region. However, a comparison between measured fast directions and APM for Region B (Figure 5b) shows that the average ϕ is not dissimilar to APM estimates for the B15 and HS3 reference frames. A model that invokes only APM-parallel shear in the asthenosphere cannot explain all aspects of the splitting behavior with stations just to the east and west. However, we cannot rule out a contribution from asthenospheric shear due to APM to the observations in this region, and it is possible that both the asthenospheric and the lithospheric upper mantle contribute.

Measurements at stations within Region C are almost totally dominated by null SKS arrivals (Figure 3), confirming an observation made by earlier studies [Long et al., 2010; Wagner et al., 2012] based on a much smaller number of stations. There are several permanent stations within Region C that exhibit clear null arrivals over the entire available backazimuthal range [Long et al., 2010], suggesting an upper mantle structure that is apparently isotropic to vertically propagating SKS phases. A more extensive analysis incorporating temporary stations by Wagner et al. [2012] found additional support for the idea that the Coastal Plain region of Virginia, North Carolina, and South Carolina is dominated by null arrivals, and we have confirmed this finding here. Although there are some stations in Region C that exhibit splitting, most are completely dominated by nulls; the backazimuthal distribution of null arrivals for Region C (Figure 5c) shows that nearly all azimuthal bins have at least 10 null arrivals. (We note that the backazimuthal distribution of nulls in Region C is not even, but is dominated by peaks near \sim 60°-80° and \sim 150°. The locations of these peaks are controlled not by structure beneath the stations but by the distribution of seismicity in the western Pacific subduction zones, as demonstrated in Figure 1b.) Interestingly, the stations in Region C that are dominated by null SKS arrivals correspond geographically to a relatively featureless portion of the magnetic anomaly map (Figure 4d; blue areas in Virginia, N. Carolina, and S. Carolina). In this region there is little variability in the magnetic anomaly, perhaps indicating a lack of major crustal structures produced by past deformation episodes.

With only 2 years of data available at most stations in this study, it would be difficult to interpret the finding of dominantly null *SKS* arrivals in this region, as many stations have a limited number of arrivals, sometimes concentrated over a narrow backazimuthal range (Figure 3). Taken as a whole, however, and in combination with previous results from permanent stations, we are confident in interpreting Region C as a region where *SKS* phases do not generally undergo splitting (or are only weakly split; at the periods used in this study, we cannot reliably detect delay times less than ~0.5 s). Many individual stations in Region C have a limited amount of data and only a few null arrivals (or a combination of null and "poor" measurements), for which the interpretation is ambiguous. However, there are many Region C stations that exhibit five or more null arrivals (white dots in Figure 4) that cover a range of backazimuths, and no split arrivals, which suggests an apparent lack of upper mantle anisotropy beneath those stations.

Long et al. [2010] articulated several possible explanations for a general lack of splitting at periods greater than 8 s in this region. These include (1) an isotropic upper mantle beneath the southeastern U.S., (2) generally complex and vertically and/or laterally incoherent anisotropy, (3) two layers of anisotropy (presumably corresponding to the lithosphere and asthenosphere) that are offset by exactly 90° and whose equal strength perfectly cancel each other out, and (4) vertical upper mantle flow (in combination with weak lithospheric anisotropy) with A-, C-, or E-type olivine fabric, which would produce weak splitting of *SKS* phases [e.g., *Karato et al.*, 2008]. *Long et al.* [2010] discussed each of these models in detail and suggested that vertical mantle flow beneath the southeastern U.S. passive continental margin was a likely explanation for the observations at permanent stations. Possible sources for vertical flow may include upwelling associated with the transport of volatiles from the Farallon slab in the midmantle [*Van der Lee et al.*, 2008] or a small-scale, edge-driven convective downwelling [*King*, 2007], which may represent a perturbation to large-scale slab driven flow beneath North America [e.g., *Forte et al.*, 2010] and may be linked to the Bermuda Rise in the Atlantic Ocean [*Benoit et al.*, 2013].

Another strong possibility is that the southeastern U.S. coastal plain exhibits very complex, vertically and/or laterally incoherent lithospheric anisotropy that obscures any deeper signal from present-day mantle flow

[e.g., *Rümpker and Silver*, 1998; *Saltzer et al.*, 2000]. For example, recent work by *Eakin et al.* [2015] using similar measurement techniques and frequency ranges as this study identified a region of dominantly null *SKS* splitting in southern Peru, which they attributed to likely small-scale heterogeneity in the lithospheric mantle. As in the *Eakin et al.* [2015] study, this interpretation would require dramatic variations on length scales smaller than the zone of maximum sensitivity (first Fresnel zone) for *SKS* arrivals (roughly 100 km in the upper mantle for a period of 8 s).

Recent work by MacDougall et al. [MacDougall, J. G., K. M. Fischer, L. S. Wagner, R. B. Hawman, Depthvarying seismic anisotropy in the southeastern United States from shear-wave splitting, in preparation for submission to Earth and Planetary Science Letters] analyzing SKS splitting at stations of the temporary SESAME experiment and surrounding TA stations yielded evidence for multiple layers of anisotropy in this region. MacDougall et al. [in preparation] included energy at higher frequencies than examined here; they used a bandpass filter of 0.05-0.35 Hz and thus included energy at periods as low as ~ 3 s, in contrast to the 8 s cutoff in this study. Because they included energy at higher frequencies than examined here, it is likely that any differences between their measurements and ours imply that SKS splitting is frequency dependent in the southeastern U.S. Previous studies have noted frequency-dependent SKS splitting in the presence of complex anisotropy [e.g., Long, 2010; Eakin and Long, 2013]. While this is a potential explanation for the preponderance of null arrivals in Region C, there is no obvious explanation for why this portion of the eastern North American lithosphere would be more complex in its anisotropic structure than other regions. Future work will be needed to resolve whether the null arrivals in Region C result primarily from complex lithospheric structure, nearly vertical present-day mantle flow, or a combination of the two. This work must encompass both new seismic observations (e.g., models of vertical variations in anisotropy derived from surface wave data; investigation of data collected offshore North Carolina from the recently completed Eastern North American Margin Community Seismic Experiment, or ENAM CSE) and detailed comparisons between the predictions made by geodynamical models of mantle flow beneath eastern North America and data sets such as the one presented here.

To the south and west of the null-dominated Region C, we observe a region (Region D) that is characterized by coherent splitting with fast directions that rotate from nearly E-W in southern Alabama and northernwestern Florida to NE-SW in southeastern Georgia and southern South Carolina. This pattern is very clearly distinct from the dominantly null *SKS* arrivals in region C, but its origin is unclear; given the clear rotation in fast directions, a model that invokes asthenospheric shear induced by APM cannot explain the range of observations, no matter what reference frame is used (Figure 5d). The clear, strong splitting with an E-W fast direction observed in southern Alabama and Georgia is a striking observation, but it does not correlate particularly well with either APM or with surface geology, leaving its interpretation unclear. The overall trend in fast directions, particularly the rotation from E-W to NW-SW to the east, is reminiscent of the shape of the Brunswick Magnetic Anomaly (BMA), which cuts E-W across Alabama and Georgia and curves to the north offshore South Carolina (Figures 1 and 4c), but the stations exhibiting this trend are not perfectly collocated with the anomaly. The BMA is thought to be an expression of the suturing of the Suwannee terrane during the Alleghanian orogeny, and/or mafic intrusions associated with Jurassic rifting within the South Georgia basin that are concentrated along the preexisting suture [e.g., *Heatherington and Mueller*, 2003; *Parker*, 2014].

Previous work using temporary stations in this region [*Wagner et al.*, 2012] suggested the possibility that stations located along the BMA and the Carolinia magnetic lineament (CML) just to the north (Figures 1 and 4c) exhibit lineament-parallel fast splitting directions that reflect lithospheric anisotropy associated with the suturing of the Suwannee and Carolinia terranes during various phases of Appalachian orogenesis. *Wagner et al.* [2012] further suggested that this prediction could be tested with the arrival of the TA in the south-eastern U.S. We find that this prediction is only partially borne out by the observations presented in this study. While we do observe some stations within Region C in North and South Carolina that exhibit fast directions parallel to the CML, in contrast to the null stations that dominate Region C, this pattern is not ubiquitous, and the correspondence between the fast directions in Region D and the BMA is less clear. We do, however, observe clear and coherent splitting in Region D that is not well explained by an APM-parallel model, suggesting that the lithosphere in this region has been deformed by past tectonic episodes, which likely include subduction and terrane accretion and may include rifting associated with the formation of the South Georgia Basin [e.g., *McBride et al.*, 1989]. Measurement of *SKS* splitting at stations of the dense SESAME Flexible Array experiment in the region that we designate as Region D reveal evidence for

anisotropy that varies laterally and/or with depth [*MacDougall et al.*, in preparation], reflecting a complex mix of past lithospheric deformation episodes.

To the west of the Appalachian Mountains, in Region E, we observe a complex mix of null-dominated stations and stations that exhibit coherent splitting, with average ϕ directions that vary spatially. Comparison with APM directions (Figure 5e) reveals that the bulk of the fast directions are rotated counterclockwise from APM, regardless of the reference frame used, so the APM model does not provide a good fit to the data in Region E. As with other regions of eastern North America, it is likely that there is a significant lithospheric contribution to *SKS* splitting in this region, but it is difficult to identify correlations with lithospheric structures. For example, the Grenville deformation front, which marks the mapped westward extent of deformation during the formation of the Rodinia supercontinent, cuts through Region E (Figure 1a), but there is no universal correspondence between its geometry and the measured ϕ . Fast directions are parallel to the Grenville Front in eastern Kentucky, but nearly perpendicular to it in northwestern Ohio (Figure 4c). Similarly, there are few obvious correlations between measured fast directions and magnetic anomalies in Region E (Figure 4d). Therefore, while it is clear that there is a significant contribution from lithospheric anisotropy in Region E, it is difficult to pinpoint the past deformation episodes or geometries that may have formed this anisotropy.

We have identified evidence for a contribution from lithospheric anisotropy in most regions of eastern North America in this study, although we can only suggest plausible causative deformation events in a few regions (e.g., Appalachian orogenesis in Region B). While the delay times documented in this study (Figure 2c) are large enough (average $\delta t = 1.1$ s) to require a contribution from the mantle and cannot be explained solely by anisotropy in the crust, it is instructive to compare the geometry of measured ϕ due to upper mantle anisotropy with crustal anisotropy. Recent work by Lin and Schmandt [2014] used measurements of Rayleigh wave ellipticity derived from ambient seismic noise at TA stations to constrain seismic anisotropy in the upper portion of the crust. At periods of 16 s, which correspond to peak sensitivity at \sim 8–10 km depth, they found evidence for strong anisotropy beneath the Appalachians with fast directions that closely follow those identified in Region B of our study, including the rotation near the Pennsylvania Salient. This correspondence is notable, and may suggest that the crust and lithospheric upper mantle beneath the Appalachians were deformed in a similar geometry during Appalachian orogenesis, resulting in similar anisotropy, or possibly that strong crustal anisotropy beneath the Appalachians is modifying the fast splitting directions due to anisotropy in the underlying upper mantle. It is worth emphasizing, however, that even if we assumed that the midcrustal anisotropy documented by Lin and Schmandt [2014] extended throughout the lower crust (for a layer of about 30 km thickness with 7% anisotropy), that would only predict SKS delay times of about 0.5 s, substantially smaller than those documented here. Furthermore, while there is good correspondence between our observations and those of Lin and Schmandt [2014] beneath the Appalachians, throughout much of the rest of eastern North America we do not observe such a correlation. Indeed, in many regions our measured fast directions are orthogonal to the crustal anisotropic geometry inferred by Lin and Schmandt [2014], including most of Region A and the northern portion of Region E.

Overall, our SKS splitting data set for TA stations in eastern North America suggests a great deal of complexity and lateral and/or vertical variability in anisotropic structure. Previous SKS splitting studies based on smaller number of stations have hinted at such variability [e.g., Levin et al., 1999; Fouch et al., 2000; Long et al., 2010; Wagner et al., 2012], but the dense station spacing and extensive geographical coverage of the TA has made it clear. The SKS splitting patterns documented in this study demonstrate the need for future work to elucidate the complex structure and constrain the relative contributions of asthenospheric and lithospheric anisotropy more tightly. Recent and ongoing data collection efforts in the region, including USArray Flexible Array experiments, the Central and Eastern U.S. network (http://ceusn.ucsd.edu), and the GeoPRISMS ENAM CSE (http://www.ig.utexas.edu/enam), will contribute to this effort. The future application of multievent splitting methods such as the splitting intensity method [e.g., Hongsresawat et al., 2015], which can robustly measure small delay times and potentially be used for imaging of anisotropic structure, will also be important. It will be essential to combine the constraints on upper mantle anisotropy beneath eastern North America derived from SKS phases with constraints from other techniques, including anisotropic receiver function analysis and measurements of surface wave dispersion. Comparisons with models of upper mantle flow beneath eastern North America will also be crucial; in this study we have focused on comparisons with APM, but detailed comparisons with models that include both plate motion and buoyancy-driven flow [e.g., Forte et al., 2010] are an important next step.

5. Summary

Measurements of SKS splitting at TA stations in eastern North America reveal evidence for contributions from both lithospheric and asthenospheric anisotropy, with a perceptible signature of lithospheric deformation associated with Appalachian orogenesis. SKS splitting delay times in eastern North America have an average value 1.1 s, close to the global average for continental regions, and do not exhibit striking lateral variations, in contrast to the fast directions. We find that measured ϕ generally do not align with APM, with the exception of some stations in the northern portion of our study area and in the Appalachians, so shearing of the asthenospheric upper mantle due to plate motion cannot be the first-order explanation for SKS splitting. We find a striking pattern of fast directions parallel to the Appalachian Mountains in a region of high topography stretching from northeastern Alabama to Pennsylvania, likely reflecting a contribution from past deformation in the mantle lithosphere. Stations in the Coastal Plain of the southeastern U.S. exhibit mainly null (that is, nonsplit) SKS arrivals over a range of backazimuths, confirming earlier findings; this observation provides an important target for future modeling studies. A region of strong, coherent splitting with generally E-W to NE-SW fast directions in the southern part of our study area may reflect past suturing events of the Suwannee and/or Carolinia terranes, although correlations with associated magnetic lineaments are imperfect. In the northern and western portions of our study area, there is evidence for lateral (and perhaps vertical) variability in anisotropic structure, with likely contributions from both lithospheric and asthenospheric anisotropy. Future work on SKS splitting in eastern North America, in combination with constraints from surface waves and receiver functions, that aims to unravel vertical and lateral complexity in anisotropic structure will be necessary to further constrain the relative contributions from the lithosphere and asthenosphere and to illuminate past and present mantle deformation.

Acknowledgments

Data supporting Figures 2-6 can be found in supporting information Tables S1-S3. Seismic waveform data from the USArray Transportable Array (TA) network were accessed via the Data Management Center (DMC) of the Incorporated Research Institutions for Seismology (IRIS). Some figures were prepared using Generic Mapping Tools [Wessel and Smith, 1999]. This work was funded by the EarthScope and GeoPRISMS programs of the National Science Foundation via grant EAR-1251515. We are grateful to Maggie Benoit, Karen Fischer, Scott King, Eric Kirby, and Lara Wagner for helpful discussions, and to Mark Panning and an anonymous reviewer for thoughtful comments.

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