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Letters

Lithospheric and asthenospheric contributions to shear-wave splitting observations in the southeastern United States

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ABSTRACT

We present observations of both null and non-null SKS splitting from temporary deployments across the southeastern United States in order to evaluate the relative contributions of lithospheric deformation and asthenospheric flow to regional anisotropy. Data for this study come from four temporary broadband seismic deployments: the Appalachian Seismic Transect (AST), the Test Experiment for Eastern North America (TEENA), the South Carolina Earth Physics Project (SCEPP), and the Florida to Edmonton Array (FLED). In general, we find fast directions aligned roughly parallel to absolute plate motion of the North American plate (APM) within and west of the Southern Appalachians, whereas to the southeast, we find a broad area dominated by complex splitting patterns consisting of well-constrained null splitting measurements over a range of backazimuths along with a very small number of resolved non-null measurements. This change in splitting patterns is consistent with a transition from drag induced asthenospheric flow beneath the older sections of the North American continent to vertical or incoherent mantle flow, likely in combination with complex lithospheric anisotropy, beneath the younger accreted terranes to the southeast. In addition to these general patterns, we find a number of non-null splitting measurements that are not aligned with APM, but are instead aligned with prominent magnetic anomalies that may correspond to ancient continental suture zones or faults. This would suggest that in these areas, a strongly anisotropic (but localized) lithospheric fabric dominates over any ambient asthenospheric anisotropic signature. In areas with generally strong APM parallel splitting, this would imply a thick sheared mantle lithosphere whose deformation-induced anisotropy is strong enough to overprint the anisotropy induced by APM, and is aligned with the shallower crustal structures responsible for generating the observed magnetic anomalies. In the southeastern areas dominated by null splitting measurements, there may be no strong signature from asthenospheric anisotropy to override, but a substantial lithospheric thickness is still required to generate the magnitude of the observed SKS splitting ($\sim$1 s). More data are required to verify these results, but future datasets including data from USArray may be able to exploit the correlations between null and non-null SKS splitting measurements and magnetic lineaments to better constrain the provenance of the regional anisotropic signature.

1. Introduction

Because of the causative link between deformation and seismic anisotropy, observations of anisotropy can provide some of the most direct observational constraints available on past and present mantle deformation (e.g., Long and Becker, 2010). Observations of seismic anisotropy in continental regions can yield particular insight into the history of past deformation episodes, as the signature of past events is often preserved in the continental lithosphere (Fouch and Rondenay, 2006). Because there may be many contributions to the observed signal from anisotropy in different depth ranges, however, the interpretation of anisotropic indicators such as SKS splitting in continental regions is not straightforward. In the eastern United States, observations of seismic anisotropy may be attributed to drag induced asthenospheric flow parallel to the absolute plate motion (APM) of the North American plate (Fouch et al., 2000), asthenospheric flow resulting from edge driven convection along the continental margin (King, 2007), asthenospheric flow associated with buoyant upwelling hydrated mantle material (Van Der Lee et al., 2008), lithospheric deformation resulting from repeated collisional events over the course of a full Wilson cycle (Vauchez and

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Barruol, 1996; Barruol et al., 1997a; Barruol et al., 1997b), or various combinations of these (Deschamps et al., 2008; Long et al., 2010).

Previous work on SKS splitting in the southeastern US has noted a pattern of fast SKS splitting that is often close to APM parallel (Barruol et al., 1997b; Fouch et al., 2000; Long et al., 2010). Long et al. (2010) also noted a contrast in splitting behavior between stations located in the Appalachian orogen and those located closer to the coast, which are often dominated by null SKS splitting over a range of backazimuths. Absolute plate motion across our study area varies depending on the reference frame used (HS3 or no-net-rotation) (Gripp and Gordon, 2002), but generally ranges between 250° and 280° (measured in degrees east of north). Fouch et al. (2000) proposed that variations in fast directions from APM can be explained by asthenospheric flow around a thick lithospheric root beneath cratonic North America. However, such a model does not explain the pervasive null splitting measurements further to the southeast observed by Long et al. (2010). These might be explained by the presence of such a cratonic keel if a sharp variation in lithospheric thickness induces localized edge-driven convection and associated vertical mantle flow (King, 2007). Vertical upper mantle flow has also been proposed beneath the east coast based not on shear-wave splitting but on tomographic S-wave velocity models that indicate the presence of a large low velocity "dike" extending from what is interpreted to be the subducted Farallon plate to the surface (Van Der Lee et al., 2008). Van Der Lee et al. (2008)propose that this low velocity anomaly represents buoyant hydrated mantle material that could help explain post-Triassic uplift along the eastern continental margin, and may eventually promote subduction initiation.

The argument for a lithospheric component to the observed anisotropy in the eastern United States is based on the short spatial scale variations in both fast directions and delay times (ϕ and δt, respectively) of splitting observations from within the orogen to areas just east of the orogen (Vauchez and Barruol, 1996; Barruol et al., 1997a; Barruol et al., 1997b). Barruol et al. (1997b) noted that the APM parallel fast directions are also parallel to local fabrics in the deformed orogenic lithosphere, and interpreted null splitting observations further east as being due to the intrusion of rifting-induced magmatism that would serve to weaken pre-existing fabrics.

Given the long and complex tectonic history of the eastern U.S., it is possible (and perhaps likely) that observed SKS splitting is due to a complex combination of several sources of anisotropy. Long et al. (2010) suggest that some degree of vertical mantle flow is likely in order to explain the large number of null splitting measurements across the area, though evidence for vertical mantle flow is not observed across the transition zone as constrained by receiver function measurements of transition zone thickness. Deschamps et al. (2008) argue for progressively frozen layers of differing asthenospheric flow patterns to explain the differing fast directions of anisotropic Rayleigh waves at different periods. Their study, however, did not extend east into the region dominated by null SKS splitting measurements. Other continental-scale studies for mantle anisotropy that include both surface wave and SKS splitting constraints have also suggested the presence of multiple layers of anisotropy in the eastern US (e.g., Yuan and Romanowicz, 2010), although given the generally poor station coverage in the area the resolution of the models in the southeastern US is likely limited.

The alignment of fast SKS splitting directions and indications of crustal deformation, such as the geometry of crustal faults, geodetic measurements, and magnetic and gravity anomalies, has been used to make arguments about the likely depth distribution of anisotropy and the vertical coherence of deformation in continental regions (e.g., Lev et al., 2006; Wang et al., 2008; Wüstefeld et al., 2010). For example, the alignment of SKS splitting fast directions and magnetic anomalies has been noted in central and northern North America (Bokelmann and Wuestefeld, 2009). Because magnetic anomalies decay as r^{-3}, they record dominantly shallower (crustal scale) structures. However, the limited thickness of the crust means it can typically account for only a few tenths of seconds of shear-wave splitting (e.g., Barruol and Mainprice, 1993; Savage, 1999; Long and Silver, 2009). If larger splitting is observed to be coincident with magnetic lineaments, this implies the presence of a thick mantle lithosphere whose anisotropic fabric is aligned with the crustal structures responsible for the magnetic anomaly.

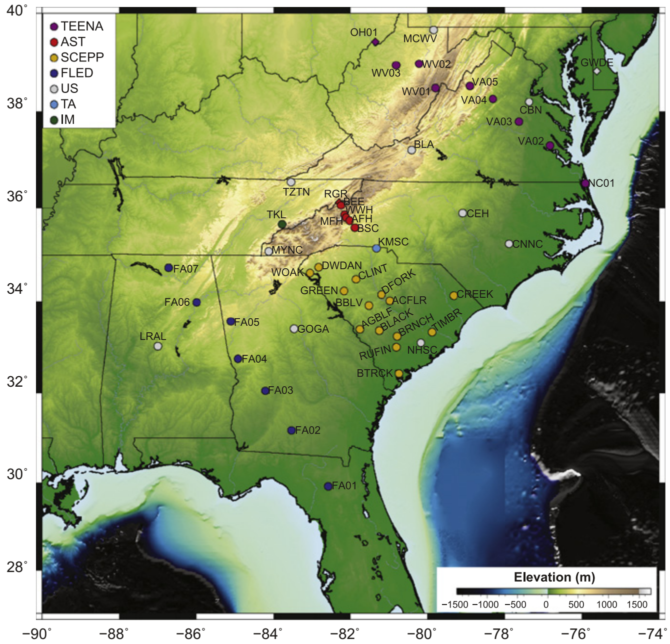

Fig. 1. Topographic map of the area showing circles at station locations, color coded by deployment/network.

Here we present new SKS splitting measurements for four temporary deployments in the southeastern US and combine them with previous results (Long et al., 2010) to produce a uniform compilation of null and non-null splitting measurements in the southeastern United States that we compare to APM, topography, surface geology, and magnetic and gravity anomalies in order to constrain the relative contributions of the lithosphere and asthenosphere to the observed anisotropy. We find predominantly null splitting measurements across broad areas in the southeastern U.S., and many APM parallel measurements further to the north and west. There are, however, a number of notable exceptions to these general patterns. Strikingly, in most of these cases, the station is located along a major magnetic anomaly or lineament, and the fast directions are anomaly/lineament-parallel. Two of these lineaments, the New York-Alabama (NY-AL) lineament (King and Zietz, 1978) and the Brunswick magnetic anomaly (BMA) (Taylor et al., 1968; McBride and Nelson, 1988) have been previously identified as possible locations of major terrane boundaries or faults. A third is more speculative, but may represent the boundary between the accreted Carolinia terrane and Grenville basement. Additional future data from the EarthScope Transportable Array and other temporary deployments will help to clarify whether this correlation between magnetic anomalies and SKS splitting is robust and to place tighter constraints on the depth distribution of anisotropy.

2. Data and methods

Data for this study come in large part from four temporary broadband seismic deployments: the Test Experiment for Eastern North America (TEENA) (Benoit and Long, 2009), the Appalachian Seismic Transect (AST) (Wagner et al., 2012), the Florida to Edmonton experiment (FLED) (French et al., 2009), and the South Carolina Earth Physics Project (SCEPP) (Frassetto et al., 2003) (Fig. 1).

The Test Experiment for Eastern North America (TEENA) consisted of 9 broadband seismometers that were deployed for a period of 11 months (August 2009–July 2010) in a roughly linear transect from Knotts Island, North Carolina to Marietta, OH. The array had an average station spacing of ~75 km and was composed of Nanometrics Trillium 120PA sensors paired with Taurus digitizer/datalogger units. The experiment, which was jointly supported by Yale University and by The College of New Jersey, was designed to traverse a variety of physiographic provinces from the Atlantic coast across the Appalachians. Eight of the nine TEENA stations yielded high-quality SKS waveforms for splitting analysis and these measurements are presented here; the westernmost station (OH01 in Marietta, OH) did not.

The Appalachian Seismic Transect (AST) consisted of 6 broadband seismometers deployed for between 12 and 16 months (April 2009–July 2010). These were installed in a transect across the Blue Ridge Mountains in North Carolina immediately south of Grandfather Mountain window, with an average station spacing of ~15 km (Wagner et al., 2012). Funding and equipment for this project came from the University of North Carolina at Chapel Hill. Of the six stations, five produced quality null or non-null SKS splitting measurements presented here. Only the westernmost station (RGR) did not. In addition to these stations, we also analyzed two other nearby stations, TKL and KMSC. TKL is part of the Miscellaneous International Network (IM), and KMSC is an advance EarthScope Transportable Array station (TA).

The Florida-to-Edmonton broadband seismometer array, in operation from June, 2001 and December, 2002, comprised 28 broadband seismometers deployed in a transect across the central United States and into Canada. These stations were included in the SKS splitting compilation for North America of Liu (2009), although null measurements were not reported in that database. In order to create a uniform data set for the southeastern US that includes nulls, we re-analyzed SKS splitting for the seven southeastern-most stations of the array, FA01–FA07. Given our geographical focus on the southeastern US, we did not include FLED stations located to the northwest of FA07 in our analysis, although they are included in the study of Liu (2009).

The South Carolina Earth Physics Project (SCEPP) consisted of 25 broadband seismometers deployed at high schools across the state of South Carolina by the University of South Carolina (Frassetto et al., 2003). The SCEPP deployment was mainly designed for educational seismology purposes and many stations suffer from large amounts of cultural noise; even with these limitations, however, the SCEPP data are usable for research applications (Frassetto et al., 2003) and we found that 14 of the 25 SCEPP stations yielded usable null or non-null splitting measurements (Fig. 1). As with the FLED stations, non-null SKS measurements for SCEPP stations were reported by Liu (2009). Most of the SCEPP stations recorded for nearly three years (September 2001–June 2004), with the exceptions of BLACK (February 2002–June 2004), CLINT (November 2001–June 2004), and CREEK (February 2004–June 2004).

In order to produce a uniform SKS splitting dataset for the southeastern United States, we followed the preprocessing procedure and measurement methods of Long et al. (2010). We selected events of magnitude ≥ 5.8 at epicentral distances between 88° and 120° for analysis (Fig. 2). A bandpass filter with

Fig. 2. Map of events used. White circles indicate event locations. White lines show great circle paths to stations that had usable null or non-null measurements from that event.

corner frequencies of 0.02 and 0.1 Hz was applied to the data; in a small minority of cases (<5%), we adjusted the higher corner frequency to 0.125 Hz to optimize waveform clarity. SKS arrivals with good waveform clarity and a minimum radial component signal-to-noise ratio of ~3 were selected for analysis. We simultaneously applied the transverse component minimization and rotation-correlation splitting measurement methods to the data using the SplitLab software package (Wüstefeld et al., 2008) and only retained non-null measurements in the data set if the measurements of the splitting parameters (fast direction ϕ and delay time δt) agreed within the 2σ error estimates. Given the relatively long characteristic periods (~10 s) of the filtered SKS phases, the lower delay time limit for splitting detection in our study is ~0.5 s (e.g., Long and Silver, 2009). Splitting measurements were given a quality ranking of "good" or "fair" following the same criteria used by Long et al. (2010); "good" quality measurements had clearly elliptical uncorrected particle motion and linear corrected particle motion, good agreement between measurement methods, and errors less than ±15° in ϕ and ±0.3 s in δt. Given the large number of null measurements at southeastern US stations identified by Long et al. (2010), we paid special attention to the characterization of null measurements (that is, SKS arrivals that exhibit no splitting). SKS arrivals with linear or nearly linear particle motion were classified as nulls; the criteria we used to define "nearly linear" particle motion is that the amount of energy on the transverse component did not exceed the noise level on the transverse component, and only measurements with low transverse component noise levels (minimum radial component signal to transverse component noise ratios of ~4, with most higher) were retained. Examples of well-constrained null and non-null splitting measurements at FLED and TEENA stations are shown in Figs. 3 and 4.

3. Results

Results for null and non-null splitting observations for the four temporary networks analyzed for this study are shown in map view in Fig. 5 (along with the measurements of Long et al., 2010) and are summarized in Supplementary Tables 1 and 2. The most

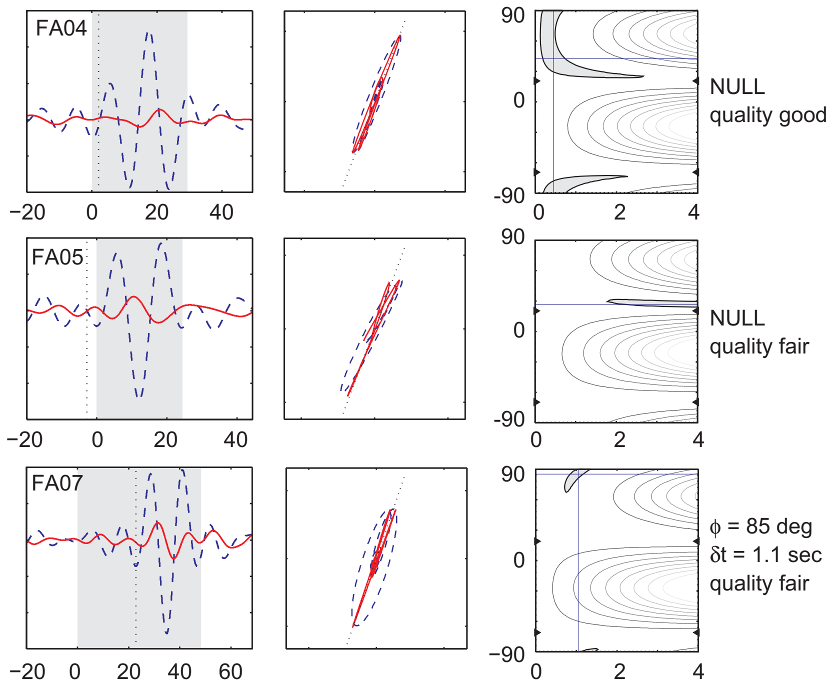

Fig. 3. Examples of splitting measurements for an event on March 3, 2002, originating in the Hindu Kush region (Mw = 7.3, epicentral distance = 105–107°, backazimuth ~20°, depth = 209 km) at three different stations of the FLED array (top panels: FA04; middle panels: FA05; bottom panels: FA07). Left panels: uncorrected radial (dashed line) and transverse (solid line) components. The gray box indicates the time window used in the analysis; the dotted vertical line indicates the expected arrival time for the SKS phase. Middle panels: particle motion diagrams for the uncorrected (dashed line) and corrected (solid line) phases. Right panels: contour plot of transverse component energy obtained for the transverse component minimization method. The gray region indicates the 95% confidence region on the splitting parameter estimates; the best-fitting splitting parameters are marked with a cross. For this event, the two stations closer to the coast (FA04 and FA05) exhibit null (or near-null) splitting; there is little or no energy on the transverse component. The furthest inland station (FA07) exhibits non-null splitting, with best fitting splitting parameters of $\phi = 68^\circ < 85^\circ < -88^\circ$ and $\delta t = 0.7\ \text{s} < 1.1\ \text{s} < 1.6\ \text{s}$.

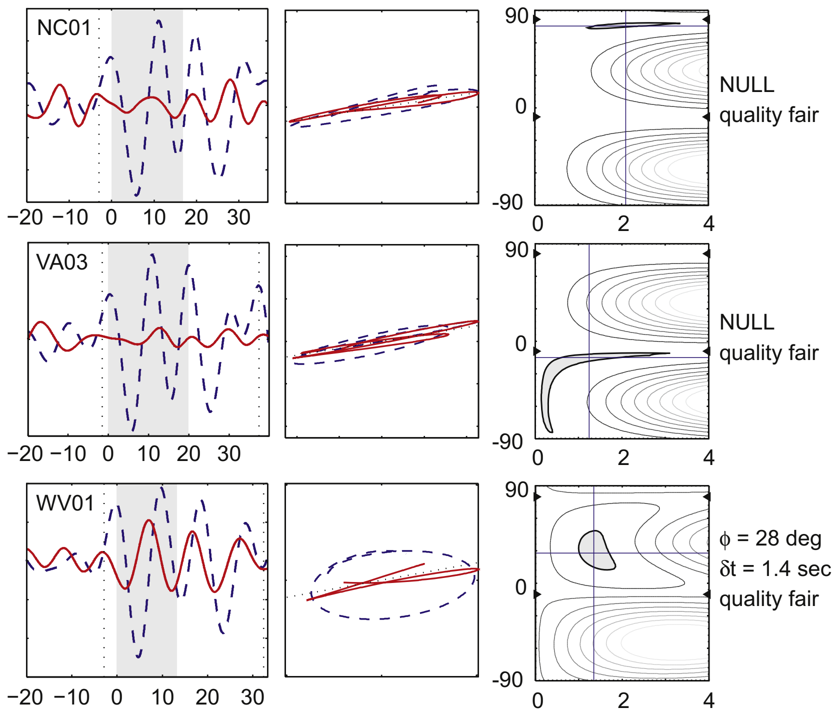

Fig. 4. Examples of splitting measurements for an event on August 30, 2009 originating in the Tonga subduction zone (Mw = 6.6, epicentral distance = 101–104°, backazimuth ~260°, depth = 10 km) at three different stations of the TEENA array (top panels: NC01; middle panels: VA03; bottom panels: WV01). Plotting conventions are as in Fig. 1. For this event, the two stations closer to the coast (NC01 and VA03) exhibit null (or near-null) splitting; there is little or no energy on the transverse component. The furthest inland station (WV01) exhibits non-null splitting, with best fitting splitting parameters of $\phi = 13^\circ < 28^\circ < -48^\circ$ and $\delta t = 1.0\ \text{s} < 1.4\ \text{s} < 1.9\ \text{s}$.

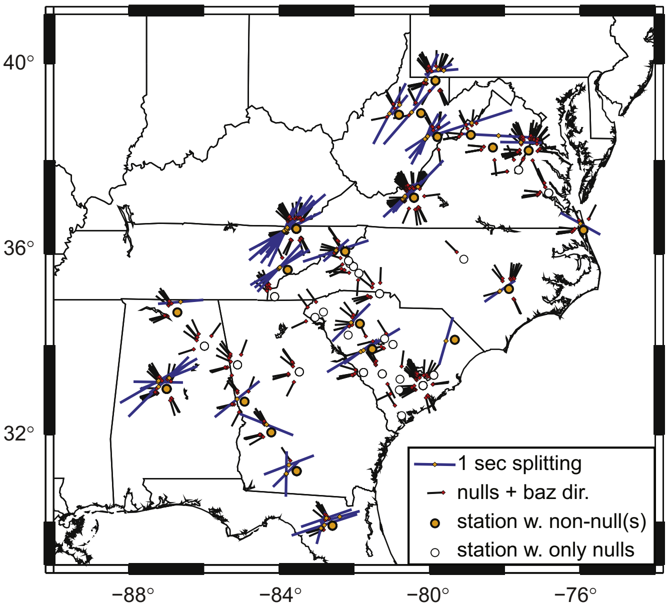

Fig. 5. Plot of all of our null and non-null measurements along with those of Long et al. (2010). Non-null splitting measurements are plotted as blue lines aligned with the fast direction (ϕ) and with their lengths scaled relative to the amount of splitting observed (δt). The center of these blue lines (indicated by the orange diamonds) is plotted at the 150 km depth pierce point for that event. Null splitting measurements are also plotted at their 150 km depth pierce points, but as red diamonds with black lines pointing in the back-azimuthal direction. White circles show stations where no non-null splitting measurements were found. Orange dots show stations where at least one non-null splitting measurement was observed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

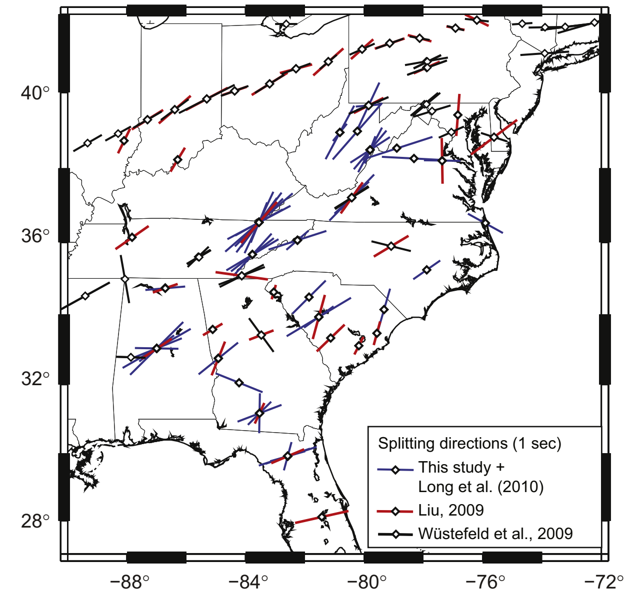

Fig. 6. Comparison plot with our measurements (blue lines) and earlier measurements. Earlier measurements are from the database of Liu (2009) (red lines), and the splitting database maintained by Géosciences Montpellier (Wüstefeld et al., 2009) (black lines). (The bulk of these data come originally from Silver and Chan, 1991; Vinnik et al., 1992; Barruol et al., 1997a,b; Fouch et al., 2000; Levin et al., 2000.) All measurements are plotted at the location of the station (white diamonds). Measurements are plotted as lines aligned with the fast direction (ϕ) and with their lengths scaled relative to the amount of splitting observed (δt). Non-null splitting measurements from our study are plotted individually; for the database measurements, we plot single-station average splitting parameters, as described in the text. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

striking first-order observation in the dataset is the preponderance of null SKS splitting measurements observed at SE US stations. Of the 206 new SKS measurements presented in this paper, 177 (86%) are classified as nulls, while only 29 showed measureable and well-constrained splitting. Similar to Long et al. (2010), we found that stations located in the western part of our study area in the Appalachian mountains tended to exhibit more non-null splitting, while stations located closer to the coast tend to be more dominated by null measurements, often over a range of backazimuths.

Stations of the TEENA deployment record many null SKS arrivals, but also exhibit non-null fast directions that appear to rotate from orogen parallel to the west to almost orogen normal in eastern Virginia. These results fill in between the results for stations MCWV and CBN from Long et al. (2010) that show a similar rotation relative to each other. Of the three easternmost TEENA stations, two record only null splitting measurements and the third and easternmost station records a single non-null measurement with a fast direction trending ESE. While the backazimuthal coverage of the null measurements at these three stations is considerably sparser than for many of the permanent stations documented in Long et al. (2010), each still exhibits nulls over a range of backazimuths; particularly at NC01 and VA03 (Fig. 5), the pattern of nulls is inconsistent with the presence of a single, simple layer of anisotropy, as discussed below.

Of the five AST stations with usable data, only the westernmost station (BEE) recorded non-null splitting measurements, both of which have fast directions roughly orogen parallel. This is consistent with previous results from nearby stations TZTN and BLA (Long et al., 2010). Station TKL also had several non-null fast directions oriented roughly orogen parallel. The backaziumthal coverage of null measurements at AST stations is sparse, with most null measurements arriving from the west (Fig. 5), although nulls from a few other backazimuths are also recorded.

Of the 14 usable SCEPP stations, eleven record only null splitting measurements, consistent with the many null measurements we observe at station KMSC, and those observed by Long et al. (2010) at station NHSC. However, three stations record a combined total of four non-null splits. Three of these are nearly parallel to those seen further to the west. A fourth is oriented very slightly east of due north. Due to the somewhat poorer data quality, the backazimuthal coverage of null measurements at individual SCEPP stations is quite sparse. Taken as a group, however, stations in South Carolina exhibit null measurements from a very wide range of backazimuths (Fig. 5).

The seven FLED stations analyzed for this study show a somewhat different pattern. Stations further to the southeast record both null and non-null splitting measurements, but the two stations most directly in line with the southern end of the Appalachians (FA05 and FA06) record no non-null splits, with nulls at these stations distributed over a side range of backazimuths from NNE to WSW directions. The westernmost station we analyzed (FA07) has one non-null observation oriented roughly E–W. These results would appear to be contradictory with the many orogen parallel fast directions observed at station LRAL by Long et al. (2010), though we note that the range of backazimuths for the null measurements at FA06 does not completely preclude fast directions oriented parallel to those of LRAL and FA04. FA03 has one observed non-null measurement whose fast direction is very different, oriented due SE. FA02 shows a range of fast directions in addition to a single null splitting measurement. Station FA01 exhibits one of the very few splitting patterns in this study that may be consistent with a single, simple layer of anisotropy, with most fast directions oriented NE–SW and null measurements coming from either the SW or the NW.

4. Comparison with previous studies

Due to the historically sparse station coverage in the eastern US, there are significantly fewer previously published results for SKS splitting in our study region than elsewhere in North America. Nevertheless, it is instructive to compare our results with those of previous studies, and such a comparison is shown in Fig. 6. We have queried the online SKS splitting databases maintained by Géosciences Montpellier (Wüstefeld et al., 2009) and by Liu (2009). The Montpellier database contains estimates of single-station average splitting parameters from various authors; for uniformity, we have estimated single-station average splitting parameters from the Liu (2009) database as well, by taking a simple average of the best-constrained individual measurements at each station. (For stations with some quality A measurements, we took the average of all A measurements; for stations with no quality A measurements, we took the average of all B quality measurements.) These single-station averages from the databases are shown in Fig. 6 along with all individual non-null measurements from this study and that of Long et al. (2010). Because null measurements are not reported in the databases of Wüstefeld et al. (2009) and Liu (2009), we do not show null measurements on this map.

In general, our measurements are consistent with those of other studies at stations located in the Appalachian mountain region, but this comparison often breaks down for stations located in the coastal plain regions of Virginia, North Carolina, South Carolina, and Georgia. Our measurements at the westernmost stations of the TEENA, AST, and FLED experiments are consistent with measurements other authors have made in the surrounding regions, with generally NE–SW fast directions. At stations located closer to the coast, however, there are often pronounced discrepancies between the measurements reported in this study and in Long et al. (2010) and measurements from the databases; indeed, there are often discrepancies between the Wüstefeld et al. (2009) and Liu (2009) databases themselves. To highlight a few examples, at station CBN in northern Virginia the average fast direction from Liu (2009) is nearly N–S, while Long et al. (2010) report one non-null measurement with a roughly E–W fast direction along with a large number of nulls over many backazimuths. At SCEPP station BBLV, we identified fast directions trending roughly NE–SW, while the average fast direction for the database of Liu (2009) is closer to N–S. At station GOGA, the Liu (2009) and Wüstefeld et al. (2009) databases report fast directions that are nearly orthogonal, while Long et al. (2010) identified only null measurements at this station covering three distinct (and non-orthogonal) backazimuths.

Some of the discrepancies among the different studies in the coastal plain region may reflect differences in preprocessing procedures, frequency content, and measurement methods among different studies, which may be pronounced (e.g., Long and Silver, 2009). The detection limit for splitting is also higher in our study ($\sim$0.5) than in studies that include energy at higher frequencies (e.g., Liu, 2009), which may explain why we do not detect some of the weaker splitting documented by other studies. However, the most likely first-order explanation for the discrepancies in this region is the presence of highly complex and laterally varying anisotropy, as discussed below. In the presence of complex anisotropy, SKS splitting patterns are complicated and exhibit significant variability with backazimuth, often along with a large number of null measurements that cover a large backazimuthal range. In this type of setting, it is a significant simplification to take a simple average of splitting parameters, and such averages may not have much physical meaning and may conflict among different studies, particularly if different frequency bands are used (e.g., Long et al., 2009).

5. Interpretation of complex splitting patterns

One of the most striking aspects of the data set presented here and that of Long et al. (2010) is the preponderance of null measurements in the overall data set and the coexistence of many null measurements, often over a large range of backazimuths, with a few well-constrained non-null measurements. In some cases, null and non-null measurements come from very similar backazimuths; at other stations (e.g., stations TZTN and WV01), non-null measurements dominate a narrow swath of backazimuths while other backazimuths exhibit null SKS arrivals. This pattern is most strikingly observed at the permanent stations examined by Long et al. (2010); due to the shorter deployment times for the temporary stations examined in this study, the splitting data set is sparser at these stations. Even at temporary stations, however, this type of complex splitting pattern is clearly seen in several instances. For example, TEENA station NC01 exhibits null splitting from NNE, NNW, and W backazimuths, along with a single non-null split from the NNW. FLED station FA04 exhibits a single non-null coming from the west, along with nulls at NNE, NNW, WSW, and SSW backazimuths.

What is the explanation for this type of unusual splitting pattern? It is clearly inconsistent with the predictions for a single layer of laterally homogeneous anisotropy with a horizontal axis of symmetry. For this case, one would expect to see consistent splitting at all backazimuths except those directions parallel and perpendicular to the fast splitting direction, which would exhibit null splitting. While many of the temporary stations examined here do not have the backzimuthal coverage to test this prediction, this type of pattern can be clearly ruled out at many of the stations in this study (e.g., FA02, FA04, CLINT, BEE, NC01, VA05, WV01, WV03) and at most of the stations examined by Long et al. (2010). For the case of multiple layers of anisotropy, one would expect to see a 90° periodicity in apparent splitting parameters (Silver and Savage, 1994). Most of our temporary stations do not have the backazimuthal coverage to test this prediction, but the analysis of Long et al. (2010) ruled out a 90° periodicity for many of the permanent stations (e.g., NHSC, CNNC, CBN, BLA, MCWV, TZTN, LRAL) throughout the region. We favor, instead, an explanation that invokes widespread lateral and/or vertical heterogeneity in anisotropic structure, most likely in the lithospheric mantle, as argued below. This type of anisotropic complexity, in which local lithospheric structures such as sutures or faults may play a role in controlling strong but highly localized deformation, can explain the highly complex and unusual splitting patterns documented in Fig. 5.

Many of the stations located in the Appalachians exhibit some degree of complexity in splitting patterns, particularly in their null distribution. However, most of these stations also exhibit a relatively large number of self-consistent non-null measurements (e.g., TZTN, BLA). Stations located in the coastal plain region tend to be even more dominated by nulls (e.g., NHSC, which exhibits only nulls, or CBN, at which Long et al. identified a single non-null measurement) and the discrepancies among different studies documented in Fig. 6 for this region indicate a high degree of anisotropic complexity relative to the mountain stations.

The transition in splitting behavior from Appalachian stations to stations located on the coastal plain was interpreted by Long et al. (2010) as evidence for a transition to primarily vertical asthenospheric flow and/or a large-scale transition in lithospheric anisotropy. Possible geodynamic scenarios that might be consistent with these scenarios are discussed in detail in Long et al. (2010), but we describe them briefly here. Two different mechanisms have been proposed as potential explanations for vertical flow at the southeastern margin of North America. One invokes edge-driven flow at the edge of cratonic North America, which would imply downwelling beneath the southeastern US and which may explain upwelling beneath Bermuda (King, 2007). A second mechanism has been proposed by Van Der Lee et al. (2008), who invoked the upwards transport of volatiles from the deep Farallon slab in the mid-mantle as an explanation for a persistent low-velocity anomaly present beneath the east coast of the US in surface wave tomography models. The vertical upwards flow implied by such a model might cause asthenospheric anisotropy with a vertical axis of symmetry beneath the region. A third possible explanation for the predominance of null splitting in the southeastern US coastal plain is the possible existence of persistent lithospheric anisotropy throughout the region with a NW–SE fast direction, would could act to cancel out any signal from APM-parallel (that is, SW-directed) flow in the asthenosphere beneath it. One possible source of such a lithospheric signal is aligned mafic dikes associated with the Triassic-Jurassic Central Atlantic Magmatic Province (CAMP; e.g., McHone, 2000), but such a mechanism would require pervasive, homogenous lithospheric anisotropy throughout the southeastern US coastal plain region.

6. Comparison between SKS splitting and crustal structures

In order to provide further constraints on the relative contributions to SKS splitting from lithospheric and asthenospheric anisotropy, we compare the splitting measurements shown in Fig. 5 from this study and from Long et al. (2010) to indicators of crustal and mantle lithospheric structure, including topography, surface geology, magnetic anomalies, and Bouguer gravity anomalies, shown in Fig. 7.

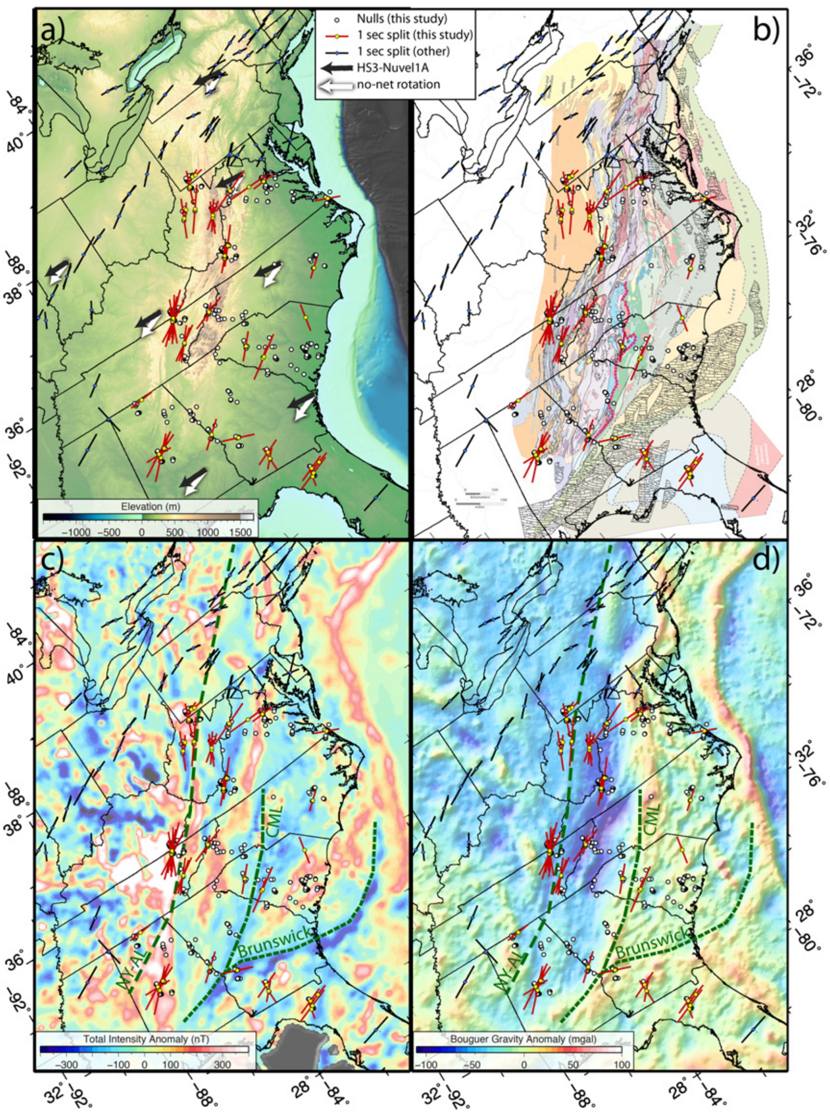

Fig. 7. Plot of SKS null and non-null splitting results on topography (a), geologic map of Hatcher et al. (2007) (b), magnetic anomalies from Maus et al. (2009) (c), and Bouger gravity anomaly from Kucks (1999) (d). Nulls are plotted as red diamonds at their 150 km depth pierce points. Non-null splitting measurements are plotted as black lines aligned with the fast direction (ϕ) and with their lengths scaled relative to the amount of splitting observed (δt). The center of the lines (indicated by an orange circle) is located at the 150 km depth pierce point for that event. Stations with only null splitting observations are plotted with white circles. Stations with at least one non-null splitting observation (regardless of nulls) are plotted with colored circles. White arrows indicate absolute plate motion using the Nuvel1A model of Gripp and Gordon (2002) in the HS3 hotspot reference frame. Black arrows show absolute plate motion also using the Nuvel1A model but in a no-net rotation reference frame. Black lines are the non-nulls from the databases of Liu (2009) and (Wüstefeld et al., 2009) plotted in Fig. 6. For clarity, we have omitted those database values located directly within our study area. In panel (b), textured shaded regions indicate Triassic rift basins. Magenta dotted line indicates the surface location of the Central Piedmont Suture. In panels (c) and (d), the green long-dashed line is plotted along the NY-AL lineament. The green short-dashed line lies along the Brunswick magnetic anomaly, and the green dashed-dot line lies along the proposed Carolinia lineament. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

6.1. Splitting along the NY-AL and Brunswick magnetic anomalies

Looking first at the topography (Fig. 7a), we note that APM, especially in the HS3 hotspot reference frame, is roughly parallel to the trend of the Appalachians especially south of central Virginia. Intriguingly, further north in Virginia along the TEENA deployment, stations further west that are orogen parallel are oriented at an oblique angle to APM, whereas the stations further east have fast directions that rotate progressively into a more APM parallel orientation. This rotation does not correlate to any obvious structural trend in the surface geology (Fig. 7b). Comparing the splitting fast directions to magnetic anomalies, however, (Fig. 7c) shows a strong correlation between proximity to the NY-AL lineament and fast directions that are lineament-parallel. With the exception of FA06 whose nulls are inconclusive due to limited back azimuthal coverage, all stations analyzed for this study, together with those of Long et al. (2010) that lie directly along the NY-AL lineament show lineament-parallel fast directions. Only the MOMA stations from Fouch et al. (2000) appear to deviate from this trend, recording dominantly APM parallel fast directions across the NY-AL lineament in northernmost Pennsylvania and southwestern New York State. In western Tennessee, the fast directions at TKL appear to be mostly parallel to the lineament. The AST station BEE has two non-null measurements, one that is generally APM parallel, and one that is generally parallel to the lineament. Comparing these trends to the gravity anomalies (Fig. 7d) shows a rough correlation between the dominant gravity low associated with much of the orogen and lineament-parallel fast directions.

We observe dominantly null measurements throughout southern Virginia, North Carolina, South Carolina, and northern Georgia. There are a few exceptions. In southern Georgia and northern Florida, FLED stations FA01–FA04 record a range of fast splitting directions. Comparing these to the magnetic lineaments shows that the unusual fast direction recorded at FA03 is in fact parallel to the trend of the Brunswick magnetic anomaly and its associated Bouguer gravity high.

The NY-AL lineament is a remarkably linear NE–SW trending magnetic gradient (Fig. 7c). It was first observed by King and Zietz (1978), but its precise location and southernmost extent was revised by Steltenpohl et al. (2010). Interpretations for the lineament range from a lithospheric scale strike slip boundary (King and Zietz, 1978; Steltenpohl et al., 2010) to the location of a Grenville-aged suture between Laurentian basement and an accreted (possibly Amazonian) terrane (Tohver et al., 2004; Mueller et al., 2008; Fisher et al., 2010) The BMA is a prominent magnetic low extending roughly E–W across Alabama and Georgia, curving to the North just offshore to join with the positive East Coast magnetic anomaly (ECMA)(Nelson et al., 1985; McBride and Nelson, 1988). This anomaly seems to define the boundary between the Gondwanan-affinity rocks of the Suwannee terrane and those of Laurentian affinity further north (Mueller et al., 1994; Heatherington and Mueller, 1999, 2003; Heatherington et al., 2010). The nature of the suture, formed during the Alleghanian orogeny, has variously been described as a south-dipping subduction zone (Nelson et al., 1985; McBride and Nelson, 1988), or transform/transpressional plate boundary (e.g., Hatcher, 2010; Heatherington et al., 2010 and references therein). While the exact nature of both the NY-AL lineament and the BMA are still the subject of ongoing research, all current models would involve lithospheric scale structures (whether sutures or major transform faults) that could involve both crust and mantle lithospheric deformation.

6.2. Splitting along the "Carolinia" magnetic lineament

The Carolinia magnetic lineament (CML) presents itself as a magnetic gradient trending NE across South Carolina and North Carolina, into Virginia (Fig. 7c). While not as pronounced as the NY-AL lineament, the Carolinia magnetic anomaly is also observed in the Bouguer gravity anomalies (Fig. 7d) where it is seen as a modest gravity high that separates the generally high valley-and-ridge textured gravity anomaly across much of the southeast from the dominant gravity low associated with the Southern Appalachians. The southern and eastern margins of this area are bounded by a similarly high gravity anomaly that parallels the Brunswick magnetic anomaly.

Between the Grenville Orogeny between 1.2 and 1 Ga (geographically located along the NY-AL lineament) and the Alleghanian Orogeny at 340–280 Ma (located along the BMA/ECMA), the east coast experienced several orogenic episodes associated with terrane accretions. Here we are particularly interested in the collision with Carolinia (Hibbard et al., 2010) (also known as the Carolina superterrane, Hatcher, 2010) that occurred either in the late Ordovician (Fig. 7b) (e.g., Hibbard et al., 2010 and references therein) or later in the mid- to late Paleozoic (e.g., Hatcher, 2010 and references therein). In either case, accretion was either accompanied or followed by dextral translation along the Central Piedmont Suture (CPS—Fig. 7b). The surface expression of this suture today is likely translated by tens to hundreds of kilometers west of its basement location, due to the formation of the Blue Ridge–Piedmont allochthon during the Alleghanian (Hatcher, 1972; Rankin et al., 1991; Keller, 1999).

The location of the Carolinia suture at depth remains uncertain. Cook and Vasudevan (2006) note the continuous nature of a shallow crustal reflector (at between 5 and 15 km depth) from the Blue Ridge to the coast and argue for the extension of Grenvillian basement as far east as the coastal plains. Others (e.g., Hibbard et al., 2007; Hibbard et al., 2010) have looked at the same seismic profile and argued for a suture between Carolinian and Grenvillian basement not far east of the surface location of the CPSZ based on a westward dipping reflector interpreted as a wedged lower half of the accreted terrane. This interpretation would be consistent with an observed wedge tectonic structure observed in receiver function common conversion point stacks calculated using data from the AST deployment (Wagner et al., 2012). It is therefore possible that the location of the Carolinia suture at depth is located just east of the suture at the surface (the CPSZ), in roughly the same location identified in the magnetic and gravity anomalies. Hatcher and Zietz (1980) make a similar suggestion correlating the cryptic Central Piedmont Suture with the western margin of an anomaly that outlines the Charlotte belt and the Carolina slate belt. This suggestion is revisited by Hatcher (2010) who correlates this magnetic anomaly with the suture between the Inner Piedmont and the Carolina superterrane.

Given this geometry for the Carolinia suture, we find it intriguing that, despite the otherwise pervasive null splitting measurements across the southeast, we find a number of fast splitting directions at stations FA04, CLINT, and BBLV that lie close to this proposed suture, all of which have fast directions that are lineament parallel (Figs. 7c and 8). We also note that station BLA has fast directions parallel to both the NY-AL lineament and the CML, but not APM. We recognize that other stations that do lie along this lineament have shown only null splitting measurements, though some are limited in the range of backazimuths observed. More data from upcoming EarthScope related seismic deployments will help to determine the robustness of this observation.

7. Discussion and summary

Our data set allows us to make several important observations about the character of shear-wave splitting and the implications

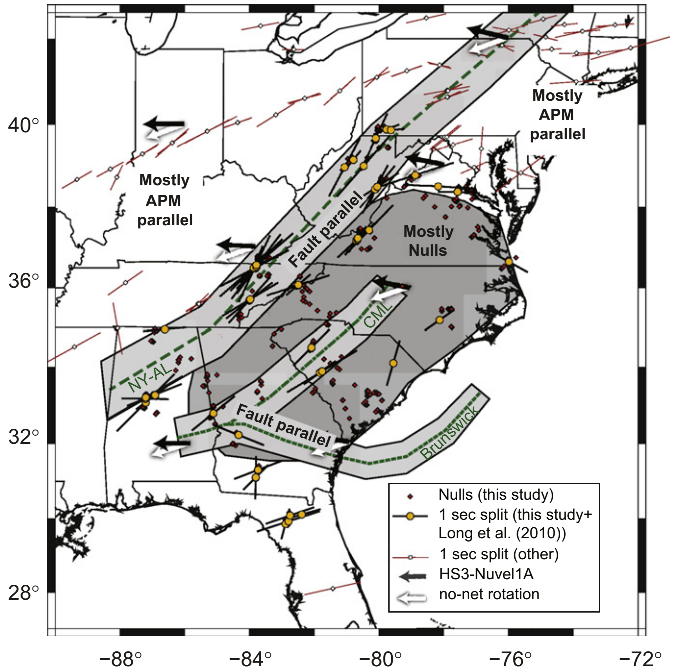

Fig. 8. Interpretive maps showing null (red diamonds) and non-null shear-wave splitting results (black lines on orange circles) from this study and those of Long et al. (2010). Thin brown lines are the non-nulls from the databases of Liu (2009) and (Wüstefeld et al., 2009) plotted in Fig. 6. For clarity, we have omitted those database values located directly within our study area. Other notations are the same as in Fig. 7. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

for lithospheric and asthenospheric anisotropy beneath the southeastern US. First, we emphasize the difference in splitting behavior between stations located within and west of the Appalachian mountains and stations located closer to the coast (Figs. 5 and 8). The former exhibit a mix of null and non-null measurements, often with fast directions that are parallel to APM, whereas the latter are dominated by null directions, with most of the few non-null measurements exhibiting fast directions that are parallel to crustal structures. Exceptions are found at three stations (CREEK, CNNC, and NC01), each of which has one non-null splitting measurement, none of which appear to align with APM, crustal structures, or magnetic or gravity anomalies. More data are required to investigate these observations. The transition from generally APM parallel fast directions to complex and generally null-dominated splitting observations indicates a significant lateral transition in asthenospheric and/or lithospheric anisotropy from the orogen to the coastal plain. The fact that SKS fast splitting directions sometimes align with APM, which implies asthenospheric shear due to plate motion, and sometimes align with crustal structures, which suggest lithospheric anisotropy due to past deformation, supports the idea that the relative contributions of asthenospheric and lithospheric anisotropy vary laterally beneath the southeastern US.

The alignment of fast splitting directions with magnetic anomalies has been observed before by Bokelmann and Wuestefeld (2009). They use a Radon transform methodology to quantify the alignment of magnetic lineaments in the Canadian shield with SKS fast splitting directions and find a very strong correlation between the two, especially in areas where magnetic lineaments align with ancient transpressive suture zones such as within the Western Superior Province. Splitting times of more than a few tenths of seconds typically cannot be explained by crustal anisotropy alone, so an alignment of magnetic anomalies (which reflect only crustal structures) and SKS splitting anomalies of 1 s or more as observed by both Bokelmann and Wuestefeld (2009) and this study must indicate coherent deformation of crust and mantle lithospheric fabric. Bokelmann and Wuestefeld (2009) argue that such vertically coherent deformation is most likely in transpressive tectonic regimes. We note that all three of our magnetic lineaments/anomalies have been postulated to be either major transform faults or transpressive plate boundaries/suture zones at some time.

Based on our synthesis of null and non-null SKS splitting and comparison with indicators of crustal structure, we propose the following model for lithospheric and asthenospheric anisotropy beneath the southeastern US. In the asthenosphere, the data are consistent with APM-parallel shear beneath the southeastern Appalachians (Fig. 8); this style of deformation has been proposed to dominate the asthenosphere beneath the North American continental interior (e.g., Fouch et al., 2000). However, the transition to splitting patterns that are dominated by null measurements at stations closer to the coast argues for a transition in asthenospheric flow; we do not see evidence for strong, coherent APM-parallel flow at stations located near the continental margin. Rather, the preponderance of null measurements at these stations indicates that anisotropy in the asthenosphere is likely absent, weak, or in a geometry that would not cause splitting of SKS phases. This is consistent with either predominantly vertical flow, as suggested by Long et al. (2010), or with asthenospheric flow that is poorly organized and results in anisotropy that is weak and/or highly heterogeneous. Another possible scenario is that the signal from any APM-induced shear beneath the coastal plain is wiped out by a coherent, large-scale lithospheric anisotropy with a NW-SE fast direction, perhaps associated with the emplacement of the CAMP, as discussed above. While this possibility cannot be completely ruled out, we view it as somewhat less likely, since our observation of localized suture-parallel SKS splits in this region suggests strong lateral heterogeneity in lithospheric anisotropy rather than a large-scale, coherent lithospheric signal.

In the mantle lithosphere, we infer strong ($\sim$1 s delay times) but very localized contributions to splitting from anisotropy that is associated with vertically coherent deformation contemporaneous with suturing events and coinciding geographically with magnetic anomalies. Elsewhere in the mantle lithosphere – that is, for regions that are geographically removed from the suture/fault zones – anisotropy is likely weak and/or highly heterogeneous, usually resulting in splitting that is close to null (or below our detection limit of 0.5 s). Generally, only in regions of intense past deformation associated with either suturing events or major transform faults is anisotropy coherent and strong enough to produce a large (but localized) contribution to SKS splitting, with fast directions parallel to the faults or sutures.

This model for lithospheric and asthenospheric anisotropy is consistent with the observations, but because of the poor depth resolution of SKS phases and the still-limited station coverage available, the data presented here cannot uniquely resolve the depth-dependent anisotropic structure beneath the southeastern US. Upcoming experiments in the region, however, should provide the data sets needed to uniquely constrain the anisotropy. With the full deployment of the TA in the eastern US beginning in 2012–2013, the data will be available to carry out detailed SKS splitting studies as well as studies of radial (e.g., Endrun et al., 2008) and azimuthal (e.g., Deschamps et al., 2008) anisotropy from surface waves and anisotropic receiver function analysis, which can identify sharp contrasts in anisotropic properties at depth (e.g., Wirth and Long, in revision). Given the preponderance of null SKS measurements observed in the southeastern US in this study and by Long et al. (2010), it is particularly important that future studies of SKS splitting using TA data pay careful attention to the characterization of null splitting. In addition to the TA, ongoing and future EarthScope FlexArray deployments in the area, including the Ozark–Illinois–Indiana–Kentucky (OIINK) project and the Southeastern Suture of the Appalachian Margin Experiment (SESAME), will provide greater density station spacing in order to determine the robustness of the patterns observed here.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.epsl.2012.06.020.

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