article submitted to JGR August 1, 1998

Shear-Wave Splitting in the Appalachians and the Urals: A Case for Multilayered Anisotropy

Vadim Levin

Yale University, New Haven, Connecticut

William Menke

LDEO, Palisades, NY

Jeffrey Park

Yale University, New Haven, Connecticut

Abstract.
Observations of shear-wave splitting in the Northeastern US Appalachians and in the foredeep of the Urals vary significantly with the back azimuth and incidence angle of the incoming phase. These variations suggest two or more layers within the upper mantle with different anisotropic properties. Synthetic seismograms for simple multilayered anisotropic structures show that shear-wave splitting parameters tend to vary substantially with the direction of approach. Relying on a subset of back-azimuth and incidence angle may strongly bias the model inferred, especially if the observations are averaged. On the other hand, the azimuthal splitting pattern provides additional constraints on vertical or lateral variation of anisotropic properties in the Earth. Using a new error-estimation technique for splitting, we find that individual measurements from broadband data have errors on the order of $\delta\phi = 3° - 7°$ for the fast direction, and $0.1 - 0.2$s for the delay of split shear waves. The azimuthal variation of splitting parameters is broadly consistent throughout the Appalachian terranes in the Northeastern US, especially for two long-running stations in the Northeast US - HRV and PAL. Observations can be separated into two distinct populations, with mean fast-axis azimuths of $N60°E \pm 4°$ and $N119°E \pm 2°$. Delay values within each population range from near-zero to $\sim$ 1s. Azimuthal splitting variation for ARU in the foredeep of Uralian mountains is characterized by sharp transitions between different groups of observations. Using synthetic seismograms in simple structures, we develop one-dimensional anisotropic models under stations HRV and ARU. The model for HRV includes two layers of anisotropic material under an isotropic crust, with fast-axis azimuths $N53°E$ and $N115°E$ for the bottom and the top layers, respectively. The model for the upper mantle under ARU includes a layer with a fast-axis at $N50°E$ atop a layer with fast-axis azimuth $N90°E$. Our modeling confirms the need for a layer of strong anisotropy with a slow axis of symmetry in the lower crust under ARU, reported by *Levin and Park* [1997a]. Our results suggest that both Urals and Appalachians possess a relict anisotropy in the tectosphere, associated with past continental collision and accretion, underlain by anisotropy with orientation similar to the local absolute plate motion, suggesting an asthenospheric component to the signal.

Introduction

Seismic anisotropy, the dependence of seismic velocity on the direction of propagation, is a common feature of modern global seismic velocity models [*Dziewonski and Anderson*, 1981] and a well documented property of olivine, the mineral that composes the bulk of the upper mantle [*Crampin et al.* 1984]. A prominent effect of seismic anisotropy is the so-called splitting of shear waves. Unlike the two shear modes in isotropic materials, which have equal phase velocities, the two corresponding modes in anisotropic materials have different velocities. As it enters an anisotropic region, a single linearly polarized shear-wave pulse will split into two pulses of different velocity. The polarizations of these pulses are related to the projection of their propagation direction onto the axes of the anisotropic elastic tensor [*Aki and Richards,* 1981].

Shear-wave splitting studies measure and describe the anisotropy of the Earth. One selects shear-wave phases that are known to be linearly polarized prior to entering the anisotropic study region, and measures their particle motion after traversing the region. One seeks a coordinate rotation that separates the particle motion into distinct "fast" and "slow" pulses, each of identical shape and linearly polarized in mutually-perpendicular "fast" and "slow" directions. The delay between the two pulses is proportional to the strength of the anisotropic effect, which depends both on the intensity of seismic anisotropy and the length of the path within the anisotropic material. The axes of the rotated coordinate system provide information on the symmetry and orientation of the anisotropic elastic tensor.

In some simple cases, such as when the tensor has hexagonal symmetry with a horizontal symmetry axis, the orientation of the fast splitting axis is approximately parallel to the symmetry axis, regardless of propagation direction. This simplification is often assumed in studies of the upper mantle. Estimates of splitting time and fast axis direction from many shear waves at a given station have been averaged to estimate anisotropic strength (i.e. delay time) and symmetry-axis azimuth for the mantle beneath that station [e.g. *Vinnik et al.*, 1995; *Barruol et al*, 1997; *Wolfe and Silver*, 1998; *Fouch et al.*, 1999]. Such "station means" are useful in tectonic settings where uniformity of the fabric in the lithosphere is likely, e.g. on the ocean floor [*Wolfe and Solomon*, 1998] or in the wake of a hot spot [*Schutt et al.*, 1998].

Station means may be quite misleading, however, in cases where both the delay time and the fast direction vary significantly with the propagation direction. Such variation can occur when an anisotropy tensor is inclined from the vertical, or has a more complicated symmetry, or both (Figure 1). *Babuska et al.*, [1993] discusses possible scenarios that involve an inclined orientation of hexagonal and orthorhombic anisotropic tensors. This possibility has also been considered by *Plomerova et al*, [1996], *Levin et al.* [1996], *Hirn et al.*, [1998] and others. Also, a combination of two or more layers of anisotropy with hexagonal symmetry and horizontal symmetry axes leads to a systematic variation of the splitting parameters with the polarization of the incoming shear wave [*Silver and Savage*, 1994; *Vinnik et al*, 1995]. For vertically incident shear waves a simple analytic expression describes the variation of splitting parameters in a simple 2-layer model, predicting a $\pi/2$ periodicity. 2-layer models with horizontal-axis anisotropy has been invoked to explain back-azimuth variations in splitting parameters [e.g., *Ozalaybey and Savage*, 1994; *Russo and Silver*, 1994; *Granet et al.*, 1998].

In this paper, we demonstrate that the fast direction and delay associated with shear waves that sample the Earth's upper mantle beneath two long-lived mountain belts vary strongly with shear-wave propagation direction. We interpret these variations in terms of multilayered anisotropy, implying either complex deformation in a past collisional event or, more plausibly, a mix of active and fossil deformations.

The parameters of a split shear wave can be estimated by a grid search over possible time-delays and fast-axis directions, and using some kind of goodness-of-fit criteria to select the "best" set of values. Two criteria have been used: 1) maximal similarity in the pulse shapes of the two rotated seismogram components, as quantified by cross-correlation [e.g., *Bowman and Ando*, 1984; *Iidaka and Niu*, 1998]; and 2) that the re-assembled "original" pulse has maximal rectilinearity, as quantified by the ratio of the rectilinear and elliptical motion [*Kosarev et al.*, 1984; *Silver and Chan*, 1991]. These two methods give the same results when tested on nearly noise-free data. Owing to their different treatment of noise, and to complications induced by multilayered anisotropy, "cross-correlation" and "rectilinearity" measures can give substantially different results when applied to noisy data.

If the anisotropic material is homogeneous, an observed split shear wave is exactly the sum of two pulses of different polarization, one delayed with respect to the other. If, in contrast, the anisotropic material consists of several layers (or, more generally, 3-D domains) of different anisotropy, then the observed seismogram has a more complicated form, with a sequence of pulses corresponding to mode-conversions from the various layer interfaces. In general, no rotation exists in which one component of the seismogram is exactly a delayed version of the other (Figure 2). Given a high-quality broadband waveform with no interfering seismic signals, these conversions could perhaps be individually identified and modeled. Unfortunately, most SKS data in studies of the upper mantle is low-passed, and resolving closely-spaced sequence of pulses is problematic.

Our approach is to retain the two parameter (fast direction and delay) description for shear-wave propagation in anisotropic media, but to recognize that this is an "apparent" measurement, without exact correspondence to an underlying physical process. This approach was introduced by *Silver and Savage*, [1994] for the case of two anisotropic layers with horizontal symmetry axes, and more recently expanded to the case of a smoothly varying medium by [*Rumpker and Silver*, 1998]. The apparent splitting parameters (Figure 3) contain significant information about the anisotropic medium. Most importantly, the apparent splitting parameters are different from what one would expect for a homogeneous medium with the same "mean" anisotropy, so that some information on the depth-dependence of the anisotropy is preserved. Unfortunately, owing to interference between the mode-conversions, the measured values of the apparent parameters are somewhat sensitive to the frequency band of the seismic data (Figure 4). *Rumpker and Silver*, [1998] show that even for a case of vertical incidence in a flat-layered model with horizontal axes of hexagonal symmetry apparent splitting parameters exhibit strong dependence on the ratio between the cumulative splitting effect of the medium and the frequency content of the shear wave. This sensitivity does not present any fundamental problem when modeling the apparent splitting. One simply compares observed apparent values with predicted ones that have been computed from synthetic seismograms with the same frequency content. However, it makes difficult the comparison of data collected by different authors using different processing schemes.

In this paper we measure apparent splitting parameters at a few locations within two Paleozoic mountain belts - the Appalachians and the Urals. We focus on the anisotropic structure of the upper mantle, and so use mostly SKS and SKKS phases. We mainly use stations with long duration of operation, and thus we are able to obtain measurements from a wide variety of azimuths and angles of incidence. As we show below, the strong directional behavior of these data indicate that the upper mantle beneath these two mountain belts possesses multiple layers of different anisotropy.

Seismic Anisotropy in the Continental Lithosphere

Silver [1996] summarizes arguments, developed over the previous decade, that anisotropy is primarily a feature of the uppermost few hundred kilometers of the Earth. This view has been recently challenged by observations of seismic anisotropy near the core-mantle boundary [*Kendall and Silver*, 1996; *Garnero and Lay*, 1997] and within the transition zone [*Vinnik and Montagner*, 1996]. Nevertheless, the presence of seismic anisotropy within the lithosphere is well-documented.

The variety of mechanisms that produce seismic anisotropy in the lithosphere centers on a handful of scenarios. In the upper crust the strongest influence is believed to be that of aligned cracks and/or pore spaces [*Babuska and Pros* 1984], for which slower velocities are found for waves that propagate normal to the average crack plane. The aspect ratio of pore/cracks and type of fluid determine the extent and proportion of anisotropy [*Hudson*, 1981; *Crampin*, 1991]. Alternating thin isotropic layers of higher and lower velocity can also produce an overall anisotropic effect [*Backus*, 1962; *Helbig*, 1994], with the velocities slower normal to the bedding than along it. In the lower crust and the uppermost mantle, cracks are assumed to close in response to increasing overburden pressure [*Babuska and Pros* 1984; *Kern et al*, 1993], though field exposures of (formerly) deep-crustal fluid-filled cracks can be found [*Ague*, 1995]. In the absence of cracks and inclusions, the lattice-preferred orientation (LPO) of mineral crystals is taken as the main cause of seismic anisotropy. Most minerals composing the bulk of the crust are anisotropic to some degree [*Babuska and Cara*, 1991], as are the olivine and orthopyroxene that predominate in the upper mantle anisotropy. Different deformation mechanisms can lead to the alignment of either the slow or the fast crystallographic direction in olivine grains [*Nicolas et al.*, 1973; *Ribe*, 1992], but LPO caused by dislocation creep in the shallow mantle is commonly believed to lead to preferred alignment of the fast axis [*Zhang and Karato*, 1995].

It is natural to expect that strain-induced seismic anisotropy would be particularly prominent in plate boundary regions, where deformations are concentrated. World-wide observations of shear-wave splitting support this notion [*Silver*, 1996]. Present-day regions of active compression commonly have fast axis of seismic anisotropy aligned sub-parallel to the strike of the orogen. One explanation for such orientation is the preferred alignment of "slow" axes of olivine along the direction of compression [*Nicolas et al.,* 1973]. *Vauchez and Nicolas* [1991] propose an alternative mechanism: preferred alignment of the olivine "fast" axes along the orogen as a result of concurrent strike-slip deformation commonly observed during mountain building.

Some stable continental interiors have anisotropic intensity equal, if not superior, to actively deforming regions, perhaps because many now-stable continental regions have experienced plate-boundary deformation in the past, and have retained a fossil deformation. Patterns of seismic anisotropy within stable continental masses may therefore record the tectonic history of these regions. Seismic stations examined in this work lie within two Paleozoic mountain belts, the Appalachians and the Uralides. Both have been loci of continent-building accretionary episodes in early Paleozoic time. Both regions are presently embedded within stable continental region, the North American and Eurasian plates, respectively.

A number of shear-wave splitting studies have examined the Northeastern US, using both permanent and temporary stations [e.g., *Silver and Chan*, 1991; *Fouch and Fischer*, 1995; *Levin et al.*, 1996; *Barruol et al.*, 1997; *Fouch et al.*, 1999]. In most cases a single "average" set of parameters was reported for selected sites (Figure 5). The average of all values shown in the map may be treated as a "regional average", and comes out as delay $\tau \sim 0.9$s and a fast direction $\phi \sim 85°$ CW from N. *Helffrich et al.* [1994] reported average splitting parameters of $\phi = N68°E$ and $\tau \sim 1$ s for station ARU, the station we examine in the foredeep of the Urals. It is interesting to note that, in both the northeastern Appalachians and the central Uralides, the fast axes of seismic anisotropy are often not parallel to the strike of the orogenic belt, and thus do not follow the pattern reported in active-tectonic regions like the Pyrenees [*Vauchez and Nicolas*, 1991] .

Splitting Parameters and Their Variance

Single seismogram estimates are needed to investigate the variation of splitting parameters with S-wave propagation direction. We use the cross-correlation method to find the parameters that best fit the model that the S-wave is composed of two pulses of identical shape but orthogonal polarization, one delayed with respect to the other.

Let us suppose that the S-wave polarization lies with the UV plane of a cartesian UVW coordinate system. For weakly anisotropic material, such as the Earth's mantle, the propagation direction will then be nearly parallel to W. In general, one might need to establish the relationship between this coordinate system and the usual $north-east-vertical$ coordinate system used to collect seismic data. However, the SKS and SKKS core phases typically used in studies of upper-mantle anisotropy have steep incidence angles, so that the UV plane is nearly horizontal (typically within 5° at the surface). The vertical component of the seismogram is often contaminated with compressional wave reverberations, so we believe it is best to use only the horizontal component data. The resulting measurement of splitting direction will be slightly biased by this approach. However the effect of this bias on earth models can be avoided simply by comparing these data to synthetic data oriented in the same fashion.

We seek to find a rotation ϕ in the UV plane, and a delay τ that maximizes the cross-correlation:

$$\begin{gathered} C(\phi,\tau) = \mathbf{u}^T\mathbf{v}/(N s_u s_v) \\ u_i = u(\phi,t_i) = \cos(\phi)U(t_i) - \sin(\phi)V(t_i) \\ v_i = v(\phi,t_i) = \sin(\phi)U(t_i-\tau) + \cos(\phi)V(t_i-\tau) \end{gathered} \tag{1}$$

where s_u and s_v are the root mean squared amplitudes of horizontal component seismograms $\mathbf{u}$ and $\mathbf{v}$, respectively, and $t_i = i\Delta t$, where Δt is the sampling interval of the seismogram. After grouping the splitting parameters into a vector $\mathbf{m} = [\phi,\tau]^T$, we denote the cross-correlation as $C(\mathbf{m})$.

We estimate the best-fitting vector $\mathbf{m}^{est}$ using a coarse grid search followed by refinement with an interpolation algorithm. We use a grid spacing of Δt in τ and 5° in ϕ. We fit (using least-squares) the cross-correlation at the maximal node and its nearest neighbors with a bi-quadratic function:

$$C(\phi,\tau) = A + B\phi + C\phi^2 + D\tau + E\tau^2 + F\tau\phi \quad (2)$$

where $A, B, C, ...F$ are constants. The maximum of $C(\phi,\tau)$ occurs at $\frac{\partial C}{\partial \phi} = \frac{\partial C}{\partial \tau} = 0$, or:

$$\mathbf{m}^{est} = \frac{[2BE - DF, 2CD - BF]^T}{(F^2 - 4CE)} \quad (3)$$

Numerical tests (not shown) indicate that this technique locates the maximum cross-correlation within $\sim$ 1% of the grid spacing, at least for seismograms with the spectral characteristics of typical SKS phases.

The uncertainty of the splitting parameters can be calculated by comparing this problem to the linearized inverse problem $\mathbf{G} \cdot \mathbf{m} = \mathbf{d}$. Here the goal is to estimate model parameters $\mathbf{m}$ and their covariance $\mathbf{C}_m$ from a data vector $\mathbf{d}$. A simple least-squares estimate of the model parameters, $\mathbf{m}^{est}$, minimizes the misfit function

$$E(\mathbf{m}) = \frac{\frac{1}{N}(\mathbf{d} - \mathbf{G}\cdot\mathbf{m})^T \cdot (\mathbf{d} - \mathbf{G}\cdot\mathbf{m})}{{s_d}^2} \quad (4)$$

Here ${s_d}^2 = (\mathbf{d}^T \cdot \mathbf{d})/N$ is the mean-squared amplitude of the data. If the data have uncorrelated error with variance ${\sigma_d}^2$, the variance of the estimated model parameters is related to the curvature of the misfit function:

$$\mathbf{C}_m = \frac{\sigma_d^2}{N{s_d}^2}\left[\frac{1}{2}\nabla_m\nabla_m E\right]^{-1}\Bigg|_{\mathbf{m}=\mathbf{m}^{est}} \quad (5)$$

(see *Menke* [1989], eqn 3.52). This equation quantifies the notion that narrow minima are associated with precise estimates. The ratio s_d/σ_d can be interpreted as the signal-to-noise ratio r_d.

We apply this formula to maximize the coherence between two seismograms $\mathbf{u}$ and $\mathbf{v}$, each of length N. The misfit function is

$$E(\mathbf{m}) = \frac{1}{2N}\left(\frac{\mathbf{u}}{s_u} - \frac{\mathbf{v}}{s_v}\right)^T \cdot \left(\frac{\mathbf{u}}{s_u} - \frac{\mathbf{v}}{s_v}\right) \quad (6)$$

where s_u and s_v are the root mean squared amplitudes of $\mathbf{u}$ and $\mathbf{v}$, respectively. This definition of misfit is algebraically equivalent to $E = 1 - C$, where $C = \mathbf{u}^T\mathbf{v}/(Ns_us_v)$ is the cross-correlation between the two data series. The variance of $\mathbf{m}$ is given by:

$$\mathbf{C}_m = -\frac{1}{Nr^2}\left[\frac{1}{2}\nabla_m\nabla_m C\right]^{-1}\Bigg|_{\mathbf{m}=\mathbf{m}^{est}} \quad (7)$$

where r is the signal-to-noise ratio (assumed the same on the two seismograms). We estimate the second derivative matrix by differentiating the quadratic interpolant (2) of the cross-correlation $C(\phi,\tau)$.

The signal-to-noise ratio can be estimated from the value of C itself, by assuming that deviations from perfect correlation are caused entirely by stochastic noise in the seismograms. Denoting this noise as $\mathbf{n}_u$ and $\mathbf{n}_v$, and $\mathbf{u}_o$ and $\mathbf{v}_o$ as noise-free seismic signals, we have:

$$C = \frac{(\mathbf{u}_o + \mathbf{n}_u)^T(\mathbf{v}_o + \mathbf{n}_v)}{|\mathbf{u}_o + \mathbf{n}_u|^{\frac{1}{2}}|\mathbf{v}_o + \mathbf{n}_v|^{\frac{1}{2}}} \quad (8)$$

We assume that the noise-free $\mathbf{u}_o$ and $\mathbf{v}_o$ are scaled versions of each other. The expected value of the cross-correlation is

$$< C >= \frac{< \mathbf{u}_o^T\mathbf{v}_o >}{\sqrt{< \mathbf{u}_o^T\mathbf{u}_o >}\sqrt{< \mathbf{v}_o^T\mathbf{v}_o >}[1 + r^{-2}]} = \frac{1}{[1 + r^{-2}]} \quad (9)$$

The estimated signal-to-noise ratio is thus $r = (C^{-1} - 1)^{-\frac{1}{2}}$.

Most time series are oversampled, and thus have correlated noise. For this case N in (3) must be replaced with the degrees of freedom $\nu < N$:

$$\mathbf{C}_m = -\left(\frac{1}{\nu r^2}\right)\left[\frac{1}{2}\nabla_m\nabla_m C\right]^{-1}\Bigg|_{\mathbf{m}=\mathbf{m}^{est}} \quad (10)$$

The degrees of freedom can be estimated by computing the autocorrelation of the normalized misfit

$$\mathbf{e}(\mathbf{m}) = \frac{1}{\sqrt{2}}\left(\frac{\mathbf{u}(\mathbf{m}^{est})}{s_u} - \frac{\mathbf{v}(\mathbf{m}^{est})}{s_v}\right) \quad (11)$$

The ratio N/ν is approximately the width of the main peak in the autocorrelation of $\mathbf{e}(\mathbf{m}^{est})$.

We have tested this method of computing covariance against Monte Carlo simulations using synthetic SKS phases that have prescribed signal-to-noise ratios in the 1:1 to 100:1 range. The results (not shown) indicate that the above methodology yields accurate estimates of variance. Standard deviations generally agree with Monte Carlo results to within 20-30%. Standard deviations are typically $3 - 7°$ for the fast axis azimuth, and $\sigma_\tau \sim 0.1 - 0.2$ s for data used in this study (Figure 6).

Shear-Wave Splitting in NE Appalachians

Figure 7 shows the pattern of SKS shear-wave splitting for two earthquakes with different back azimuths (westerly and northwesterly), observed at all available seismic stations in the NE Appalachian region. The observed shear-wave fast directions differ for the two back azimuths. The event with westerly back azimuth has a northeasterly fast direction, while the event with the northwesterly back azimuth has an easterly fast direction. The fast direction appears to be a rapidly-varying function of back azimuth. Variability is also seen across the region for each event, indicating that some lateral heterogeneity is present. This heterogeneity was characterized by *Levin et al.* [1996] in terms of differences between "Appalachian" and "Grenvillian" provinces.

We compiled SKS splitting data for the two longest-running of these stations, HRV (Harvard, MA) and PAL (Palisades, NY) (Figure 8). We used observations of SKS, $SKKS$ and PKS phases, as well as a few S_{diff} and S phases from deep-focus events. Core phases (SKS and the like) are SV-polarized by the P-S conversion at the core-mantle boundary, and are useful for the study of the seismic anisotropy in the upper mantle and lithosphere. In the interest of broadening the azimuthal coverage of our dataset we also used S and S_{diff} phases from medium-sized events with hypocenters deeper then 500 km. We assume that these phases encounter anisotropy only in the "receiver-side" upper mantle and the lithosphere. We also note that splitting parameters obtained for S_{diff} phases (two observations for HRV, three observations for PAL) closely match splitting parameters obtained for SKS phases from same events. Thus potential contamination of the S_{diff} signal by the D'' anisotropy [*Garnero and Lay*, 1997] does not seem strong along these particular paths.

The data for these two stations are quite similar (Figure 9). Fast direction azimuths tend to fall into the northeasterly and easterly populations discussed above, resulting in a bimodal distribution of the azimuthal angle between pairs of measurements (Figure 10). The assumption of two populations (with mean azimuths of $N60°E \pm 4°$ and $N119°E \pm 2°$) is statistically superior to the assumption of only one population (with mean azimuth of $N95°E \pm 5°$) at the 99.9% significance level (computed via the F-test). The means of these two populations are also different at the 99.9% significance level (computed via the t-test). We have examined the SKS seismograms that were used as input to the splitting parameter estimation procedure (Figure 11). No anomalies that might cause spurious parameter estimates are apparent, giving us confidence that observed variation of splitting parameters is real.

Barruol et al. [1997] measured shear-wave splitting at HRV using several of the earthquakes in our data set. They report $\phi = N86°E(orN89°E), \tau = 0.99s(or0.65s)$ (values given for two different processing techniques). This result is quite similar to our "single population" mean of $N95°E$. It is interesting to note that the plot of all HRV data in *Barruol et al.* [1997] (their Figure 5) and the table listing individual values (electronic supplement table 2) contain members of both populations of fast directions. Another analysis of HRV data was done by *Fouch and Fischer* [1995] to compare with data from the MOMA portable array, but included only those events that occurred while the array was active (1995 through early 1996). They reported an average $\phi = N118°E, \tau = 1.13$s, similar to our mean over easterly back-azimuths ($N119°E$). In both cases the measured average value is biased by the event distribution, which is dominated by northwesterly events from NW Pacific earthquakes. The discrepancy in reported sets of splitting parameters most likely reflects differences in the distribution of data with back azimuth. Although of dubious value given the systematic fluctuations of the data, the mean value of the splitting direction (calculated as a model result, and discussed below) is $N89°E$, which matches the ϕ value reported by *Barruol et al.* [1997].

We modeled the seismic data using splitting parameters derived from synthetic seismograms of SKS phases. We compared two different algorithms for computing the synthetic seismograms in vertically stratified, anisotropic media: a propagator matrix method [*Levin and Park*, 1997b], and a ray method. Both give near-identical results. We use a grid-search over anisotropic parameters to find a best-fitting earth model, where the goodness-of-fit criteria minimizes the misfit

$$E = \sum_i \frac{({\tau_i}^{observed} - {\tau_i}^{predicted})^2}{{\sigma^2}_\tau} + \frac{({\phi_i}^{observed} - {\phi_i}^{predicted})^2}{{\sigma^2}_\phi}$$

Here σ_τ and σ_ϕ are the standard deviations of the delay time τ and fast azimuth ϕ, respectively. We have examined two classes of earth models: one or two anisotropic mantle layers placed between an isotropic crustal layer and an isotropic mantle halfspace. We search only for the thickness of the layers and the orientation of the anisotropic tensors. The anisotropic medium is constrained to consist of 30% orthorhombic olivine and 70% isotropic olivine, a mixture that is about 6% anisotropic for shear waves. The best-fitting one-layer model has an anisotropic layer that is 58 km thick, and the two layer model has top and bottom layers that are 60 and 90 km thick, respectively. Parameters for our preferred hexagonally symmetric model are indicated in Table 1. Tensor orientations for our preferred orthorhombic model are indicated in Table 2 and Figure 12. Both hexagonal and orthorhombic two-layer models correctly capture the variation of splitting parameters with back azimuth, while the one-layer models do not. Figure 13 compares results for the 1- and 2-layer orthorhombic models. The variance reduction of the two-layer model is roughly three times greater than the one-layer model, an amount that is statistically significant to the 99% level (computed via the F-test). The two-layer orthorhombic model gives fast-axis azimuths of $N53°E$ and $N115°E$ for the bottom and top layers, respectively, which are close to the means of the two observed azimuthal populations. The fast-axis strikes for hexagonal symmetry are only slightly different, at $N50°E$ and $N100°E$ for the bottom and top layers, respectively. However, the symmetry axes are tilted: only 15° above the horizontal in the top mantle layer, but 40° below the horizontal in the lower layer.

To test whether the symmetry-axis tilts are significant we compare the observed back-azimuth pattern of the apparent fast direction with those predicted by our hexagonal and orthorhombic models, and also by the 2-layer splitting operator of *Silver and Savage* [1994] (Figure 14). To construct the operators, we computed the delays τ_k a vertically-incident shear phase would experience in each layer of the orthorhombic and hexagonal models, and used respective fast directions. Predicted patterns are quite similar although, as one would expect, the approximation and synthetics show greatest difference at discontinuities in the pattern, where waveform complexity is the greatest. Also, patterns from forward modeling are only approximately periodic because of the tilts of the anisotropy axes. These violations of $\pi/2$ periodicity may possibly serve as diagnostic traits in choosing the preferred model. Our present collection of data is too limited to uniquely resolve the tilt of the symmetry axes, though they seem to prefer some deviation from the horizontal.

The broad spatial coherence of shear-wave directions throughout the NE Appalachians (as evidenced in Figure 5) suggest that there is a strong vertical stratification of the anisotropy in the upper mantle beneath that region. Earth models with two anisotropic upper-mantle layers can fit the observed SKS splitting data well. More complicated vertically-stratified models cannot be ruled out, but are not required by the data. Some lateral heterogeneity is also present in the splitting data. We note, however, that even large heterogeneity in the splitting data does not necessarily translate into large heterogeneity in structure. Given the quick variation of the parameters with back azimuth, just a few degrees rotation of either the earth model or the incoming shear wave can lead to widely different values of the splitting parameters. A complete characterization of any 3-D "anisotropic domains" responsible for the observed lateral heterogeneity will require extensive back-azimuth coverage at many stations.

We interpret the top anisotropic layer to represent the continental lithosphere associated with the Appalachian orogen, and the bottom layer to represent the asthenosphere. A conceptual model of layered anisotropy under HRV is presented on Figure 15. Alignment of the fast axes of olivine in the upper layer is near-normal to the strike of geomorphological features in New England, where the trend of the Appalachians rotates from northeast to north. The alignment in the lower layer of the model is more in line with the overall strike of the Appalachian Orogen, as well as the hypothetical "edge" of the North American cratonic keel.

Shear Wave Splitting at Station ARU in the Foredeep of Urals

The GSN station ARU (Arti, Russia) is located on the easternmost edge of the East European platform (Figure 16), in the Uralian foredeep [*Ivanov et al.* 1975; *Zonenshain et al.* 1984] that accumulated sediments in a passive continental margin setting through most of the Paleozoic. The continental collision at the final stage of Uralian orogeny formed an extensive thrust-sheet complex to the east of ARU, and may also have deformed the sediments underlying ARU. [*Levin and Park*, 1997a] studied crustal anisotropy beneath ARU using the anisotropic receiver function method. This method, which utilizes $P-S$ conversions in layered media, is sensitive to anisotropy adjacent to interfaces where the conversions occur. *Levin and Park*, [1997a] show that receiver function data are consistent with a vertically-stratified earth structure in which both the uppermost and the lower crust are anisotropic, with hexagonal symmetry and strong tilt in the symmetry axes. Unlike typical models of seismic anisotropy in the mantle, the crustal model for ARU contains a layer of anisotropy with a slow symmetry axis. A conceptual model that would exhibit this type of anisotropy is a layer of imbricated peridotite and metapelite lenses in the region of the crust-mantle transition, as described by *Quick et al.* [1995] in the Ivrea deep crustal exposure in the Alps. Upper mantle anisotropy under ARU has previously been studied by *Helffrich et al*, [1994], who report a mean fast axis strike of $N68°E$ and a splitting time $\tau \sim 1$ s.

We have compiled splitting data from SKS and other core-refracted phases for this station (Figure 17). Several populations of fast-axis strikes are evident. For example, events from the northwest have westerly strike, while those from the east have more northwesterly strike. The best-fitting one-layer anisotropic earth model (Figure 18, top), with fast-axis at $N73°E$ azimuth, does not reproduce this pattern well. A combination of the *Levin and Park* [1997a] crustal model with the mantle model of *Helffrich et al.* [1994], does better (not shown), but does poorly at the ENE back azimuths. A model with a second mantle layer improves the fit significantly (Figure 18, bottom). This best-fitting model (Table 3) has a 58 km upper mantle layer with a fast-axis striking $N50°E$ atop a 140 km layer with fast-axis plunging 40 ° to the east (Figure 19).

Figure 20 illustrates a conceptual model of anisotropic layering under ARU. Lower crust and uppermost mantle under the Uralian foredeep are characterized by the common direction of anisotropy $\sim 50°$, which is significantly oblique to the trend of Urals. It may be related to the deformation within the East European platform that predates the formation of the orogen. The anisotropy-inducing fabric in the lower part of the lithosphere is aligned nearly normal to the strike of the Uralian Orogen.

Discussion of Geodynamic Implications

In both Appalachians and Uralides we find evidence for at least two distinct layers of seismic anisotropy in the mantle. The exact depth and thickness of layers is subject to assumptions about the percent of aligned minerals within the volume. Anisotropic intensities in our models follow measurements done on hand-samples of peridotite from ophiolites [*Christensen*, 1984], and are likely to represent the upper bound in percent of alignment. If the alignment of minerals is weaker, the required thicknesses of the anisotropic layers will increase. The tilt of inferred anisotropy-inducing fabric with respect to the horizontal is a function of the symmetry system chosen for the anisotropy. For the Appalachian stations, both orthorhombic anisotropy, with nearly horizontal fast axes, and hexagonal anisotropy, with tilted fast symmetry axes, satisfy the data. We suspect that this tradeoff will be common in studies of this type, and difficult to resolve without a clear indication of the best symmetry choice from mineral texture studies. Significantly, in both modeling exercises the horizontal azimuth of the fast axis does not depend on the symmetry system and the method of computing synthetic seismograms. We thus believe that robust elements of our models are the minimum number of anisotropic layers, their vertical sequence, the orientation of fast direction and the cumulative anisotropy within each of them.

The overall regional consistency of observations in the Northeastern Appalachian region (Figure 7) argues against a "local" character for shallow-mantle structures revealed by shear-wave splitting. Rather, the structure modeled using the HRV dataset appears to be common to the area of Appalachian terranes. On the other hand, some regional variation is present (e.g., *Levin et al*, [1996]). Whether it is caused by the "true" lateral variation in anisotropic features of the subsurface, or simply reflects changes in geometry of observation, is an open question.

In case of the Uralian foredeep we have a "spot" measurement, and arguing for its regional extent is harder. Major geologic structures of the Ural Orogen are very consistent along strike, making it almost 2-dimensional. An average splitting direction of 0° (sub-parallel to the strike of the Urals) reported by [*Vinnik et al.*, 1992] at the station SVE near Yekaterinburg (Figure 16) falls on the opposite side of the main Uralian Fault Zone. This major suture divides accreted terranes from the East European Platform [*Zonenshain et al.*, 1984]. The splitting at SVE most likely reflects a different structure in the crust and the uppermost mantle.

Given the uncertainties discussed above, the interpretation is necessarily tentative. If we consider the anisotropy to be "frozen in" or "fossil," confined within the continental keel, in both Appalachian and Urals we may infer at least two distinct past tectonic episodes. *Abbott* [1992] describes a conceptual model for accumulating material with different deformation fabrics within the body of a continent, via underplating the continent with oceanic-plate material during successive episodes of subduction. A similar model, only with oceanic "slabs" stacked in the lateral direction, has been advocated for Western Europe [e.g. *Babuska et al.*, 1993, *Plomerova et al*, 1996]. The "frozen fabric" explanation appears plausible for the upper layers in both modeled regions. In Urals the lowermost crust has the same orientation ($N50°E$, from *Levin and Park* [1997a]) as the upper layer of our mantle model. Interestingly, the sense of anisotropy reverses from the crust (slow axis) to the mantle (fast axis). We believe that crustal anisotropy in the crust is imposed by fine layering of materials with contrasting properties, while in the mantle it is imposed by preferred alignment of peridotite minerals. The strike of fabric in lower crust and uppermost mantle under ARU is oblique to the strike of the orogen, and may reflect a tectonic episode predating its formation. Analysis of crustal $P-SH$ conversions [*Levin and Park*, 1997b] under HRV did not reveal strong crustal anisotropy of the kind seen under ARU. The upper layer of the mantle anisotropy has fabric orientation that is roughly normal to the geomorphological features and main tectonic boundaries in the region. Numerous subduction episodes, both east-verging and west-verging, took place during the formation of the Appalachians, and the fabric we reconstruct is likely to be a remnant of one of them.

An alternative mechanism for anisotropy in the mantle – active flow in the asthenosphere [e.g., *Vinnik et al*, 1992] – appears more suitable for the lower layers in our models. For the Appalachians the strike of fabric in the lower layer of our model aligns closely with the absolute plate motion vector of $\sim N65°E$ [*Gripp and Gordon*, 1990]. It also aligns with the hypothetical edge of the North American continental keel. The keel edge would direct the orientation of asthenospheric flow if one assumes that mantle moves "west" relative to the North American craton, and around its keel [*Fouch et al.*, 1999]. The Urals are located in the middle of the Eurasian continent which is near-stationary with respect to the hotspot reference frame. The direction of possible motion for Eurasia is approximately east-west, if one ignores the error bars on the rate of motion in *Gripp and Gordon*, [1990]. This direction, though poorly constrained, aligns with the fast axis of the lower layer in the anisotropic structure we infer under ARU.

Our results clearly contradict the notion that fast-axis strike for shear-wave splitting in a region of compressional deformation should align with the strike of the orogen [*Vauchez and Nicolas*, 1991; *Nicolas*, 1993; *Vauchez and Barruol*, 1996]. In two regions of Paleozoic deformation we find patterns of seismic anisotropy consistent with vertically heterogeneous anisotropic structure. It is possible that in such complex regions a subset of measurements will indeed line up with the strike of an orogen. Our experiments with multilayered anisotropic structures show that direct mapping of splitting parameters (or their averages) onto tectonic features can be misleading.

Conclusions

Observations of shear-wave splitting in the Northeastern US Appalachians and in the foredeep of the Urals vary significantly with the back azimuth and incidence angle of the phase. To analyze these datasets properly we developed a new technique for estimating uncertainties of splitting parameters. Using this technique we find that typical errors of the shear-wave splitting parameters determined from low-passed broadband data from GSN station HRV are $3° - 7°$ for the fast direction, and $0.1 - 0.2s$ for the delay.

Experiments with synthetic seismograms generated in simple multilayered anisotropic structures show that splitting parameters tend to vary significantly with the back-azimuth of the analyzed shear wave. A restricted subset of back azimuths may strongly bias any model derived from observations, especially if the observations are averaged. On the other hand, the azimuthal variation pattern provides important constraints on vertical or lateral variation of anisotropic properties in the Earth.

On the basis of data from well-recorded events with different back azimuths, splitting parameters appear to be broadly consistent throughout the Appalachian terranes in the Northeastern US. (This consistency weakens for stations west of the Appalachians.) A close similarity in back-azimuth dependence of splitting parameters is found in data from two long-running stations in the Northeast US - HRV and PAL. Good back-azimuth coverage at these two stations allows us to separate observations into two statistically significant populations. Within these populations mean azimuths are $N60°E \pm 4°$ and $N119°E \pm 2°$, and delay values vary within each population from near-zero to $\sim 1s$. The exact values of delays, as well as individual estimates of fast direction, are affected by the filter parameters chosen when low-passing. The back-azimuth dependence of splitting parameters for the station ARU near the Urals is characterized by sharp transitions between different groups of observations.

Using synthetic seismograms computed in flat-layered media we developed one-dimensional models of seismic anisotropy distribution under stations HRV and ARU. The model for HRV contains two layers of anisotropic material under an isotropic crust, with fast-axis azimuths of $N53°E$ and $N115°E$ for the bottom and the top layers, respectively. Depending on the choice of symmetry for the elastic tensors, these axes are tilted (hexagonal symmetry) or near-horizontal (orthorhombic symmetry). Assuming 30% orthorhombic olivine and 70% isotropic olivine, a mixture that is about 6% anisotropic, the vertical dimensions are 60 and 90 km for the top and bottom layers, respectively. The model for ARU includes crustal structure that was constrained using Ps converted phases [*Levin and Park*, 1997a]. Assuming hexagonal symmetry of the upper mantle anisotropy, the model for ARU predicts a ~ 60 km layer with a fast-axis at $N50°E$ atop a 140 km layer with a fast-axis plunging 40° towards $N90°E$.

The analysis performed in this paper was made possible by good azimuthal coverage of observations. These are generally obtainable through prolonged observation. Data from short deployments, even in stable continental regions, apparently run the risk of bias from an uneven distribution of seismicity.

Acknowledgments. We used **GMT** software [*Wessel & Smith,* 1991] to prepare figures. Comments by Matt Fouch, Ray Russo and 2 anonymous reviewers helped improve this paper. We thank Matt Fouch for providing a copy of *Fouch et al.*, [1999] prior to publication. This work has been supported by NSF grant EAR-9707189.

References

Abbott, D., The case for accretion of the tectosphere by buoyant subduction, *Geophys. Res. Lett., 18*, 585–588, 1992.

Ague, J. J., Deep crustal growth of quartz, kyanite and garnet into large aperture, fluid-filled fractures, northeastern Connecticut, USA, *J. Metamorphic Geology, 13*, 299–314, 1995.

Aki, K., and P. G. Richards, *Quantitative Seismology*, W. H. Freeman, San Francisco, 1981.

Babuska, V., and Z. Pros, Velocity anisotropy in granodiorite and quartzite due to the distribution of microcracks, *Geophys. J. R. Astron. Soc., 76*, 121–127, 1984.

Babuska, V., and M. Cara, *Seismic Anisotropy in the Earth*, Kluwer Academic, Dordrecht, 1991.

Babuska, V., J. Plomerova, and J. Sileny, Models of seismic anisotropy in the deep continental lithosphere, *Phys. Earth Planet. Inter., , 78*, 167–191, 1993.

Backus, G. E., Long-wave elastic anisotropy produced by horizontal layering, *J. Geophys. Res., 67*, 4427–4440, 1962.

Barruol, G., P. G. Silver and A. Vauchez, Seismic anisotropy in the Eastern United States; deep structure of a complex continental plate, *J. Geophys. Res., 102*, 8329–8348, 1997.

Bostock M. G. and J. Cassidy, Variations in shear wave splitting across the canadian National Seismic Network, *Geophys. Res. Lett., 22*, 5-8, 1995.

Bowman, J. R. and M. A. Ando, Shear-wave splitting in the upper mantle wedge above the Tonga subduction zone, *Geophys. J. R. Astron. Soc., , 88*, 25–41, 1987.

Crampin, S., E. M. Chesnokov and R. G. Hipkin, Seismic anisotropy - the state of the art: II, *Geophys. J. R. Astron. Soc., , 76* , 1–16, 1984.

Crampin, S., Wave propagation through fluid-filled inclusions of various shapes: interpretation of extensive-dilatancy anisotropy, *Geophys. J. Int., 104*, 611–623, 1991.

Christensen, N. I., The magnitude, symmetry and origin of upper mantle anisotropy based on fabric analyses of ultramafic tectonites, *Geophys. J. R. Astron. Soc., 76*, 89–111, 1984.

Dziewonski, A. M., and D. Anderson, Preliminary reference earth model, *Phys. Earth Planet. Inter., , 25*, 297–356, 1981.

Fouch, M. J., and K. M. Fischer, A search for split shear waves beneath the Eastern United States, *EOS*, *76*, 412, 1995.

M.J. Fouch, K.M. Fischer, and E.M. Parmentier, Shear-wave splitting, continental keels, and patterns of mantle flow, submitted to *J. Geophys. Res., ,* 1999.

Garnero, E. J., and T. Lay, Lateral variations in lowermost mantle shear wave anisotropy beneath the North Pacific and Alaska, *J. Geophys. Res., 102*, 8121–8135, 1997.

Granet, M., A. Glahn and U. Achauer, Anisotropic measurements in the Rhinegraben area of Massif Central: Geodynamic implications, *PAGEOPH, 151*, 333-364, 1998.

Gripp, A. E., and R. G. Gordon, Current plate velocities relative to the hotspots incorporating the NUVEL-1 global plate motion model, *Geophys. Res. Lett., 17*, 1109–1112, 1990.

Helbig, K., *Foundations of Anisotropy for Exploration Seismics*, Pergammon/Elsevier Science, Oxford, 1994.

Helffrich, G., P. G. Silver, and H. Given, Shear-wave splitting variation over short spatial scales on continents, *Geophys. J. Int.*, , *119*, 561–573, 1994.

Hirn, A., J. Diaz, M. Sapin and J.-L. Veinante, Variation of shear-wave residuals and splitting parameters from array observations in southern Tibet, *PAGEOPH, 151*, 395-405, 1998.

Hudson, J. A., Wave speeds and attenuation of elastic waves in material containing cracks, *Geophys. J. R. Astron. Soc., 64*, 133–150, 1981.

Iidaka, T. and F. Niu, Evidence for an anisotropic lower mantle beneath eastern Asia; comparison of shear-wave splitting data of SKS and P660s, *Geophys. Res. Lett., 25*, 675-678. 1998.

Ivanov, S. N., A. S. Perfiliev, A. A. Efimov, G. A. Smirnov, V. M. Necheukhin, and G. B. Fershtater, Fundamental features in the structure and evolution of the Urals, *Amer. J. Sci., 275A*, 107–130, 1975.

Kendall J. M. and P. G. Silver, Constraints from seismic anisotropy on the nature of the lowermost mantle, *Nature*, *381*, 409–412, 1996.

Kern, H., C. H. Walther, E. R. Fluh, and M. Marker, Seismic properties of rocks exposed in the POLAR profile region - constraints on the interpretation of the refraction data. *Precambrian Research 64*, 169–187, 1993.

Kosarev, G. L., L. I. Makeyeva, and L. P. Vinnik, Anisotropy of the mantle inferred from observations of P to S converted waves, *Geophys. J. R. Astron. Soc., 76*, 209–220, 1984.

Levin, V., W. Menke, and A. L. Lerner-Lam, Seismic anisotropy in northeastern US as a source of significant teleseismic P traveltime anomalies, *Geophys. J. Int.*, , *126*, 593–603, 1996.

Levin, V., and J. Park, Crustal anisotropy in the Ural Mountains foredeep from teleseismic receiver functions, *Geophys. Res. Letts., 24*, 1283–1286, 1997a.

Levin, V., and J. Park, P-SH conversions in a flat-layered medium with anisotropy of arbitrary orientation, *Geophys. J. Int.*, , *131*, 253–266, 1997b.

Menke, W., Geophysical Data Analysis: Discrete Inverse Theory, Revised Edition, *Academic Press*, New York, 1989.

Nicolas, A., Why fast polarization directions of SKS seismic waves are parallel to mountain belts, *Phys. Earth Planet. Inter.,* , *78*, 337–342, 1993.

Nicolas, A., F. Boudier, and A. M. Boulier, Mechanism of flow in naturally and experimentally deformed peridotites, *Am. J. Sci.*, *10*, 853–876, 1973.

Ozalaybey, S., and M. K. Savage, Double-layer anisotropy resolved from S phases, *Geophys. J. Int.*, *117*, 653-664, 1994.

Park, J., 1996. Surface waves in layered anisotropic structures, *Geophys. J. Int.*, *126*, 173–183.

Plomerova, J., J. Sileny and V. Babuska, Joint interpretation of upper-mantle anisotropy based on teleseismic P-travel time delays and inversion of shear-wave splitting parameters, *Phys. Earth Planet. Inter.,* , *95*, 293–309, 1996.

Quick, J. E., S. Sinigoi and A. Mayer, Emplacement of mantle peridotite in the lower continental crust, Ivrea-Verbano zone, northwest Italy, *Geology, 23*, 739–742, 1995.

Ribe, N., On the relation between seismic anisotropy and finite strain, *J. Geophys. Res., 97*, 8737–8747, 1992.

Rumpker, G. and P. G. Silver, Apparent shear-wave splitting parameters in the presence of vertically varying anisotropy, *Geophys. J. Int.*, , 790–800, 1998.

Russo, R., and P. G. Silver, Trench-parallel flow beneath the Nasca Plate from seismic anisotropy, *Science, 263*, 1105–1111, 1994.

Silver, P. G., and M. K. Savage, The interpretation of shear-wave splitting parameters in the presence of two anisotropic layers, *Geophys. J. Int.*, *119*, 949–963, 1994.

Silver, P. G., and W. W. Chan, Shear-wave splitting and subcontinental mantle deformation, *J. Geophys. Res., 96*, 16429–16454, 1991.

Silver, P. G., Seismic anisotropy beneath the continents: Probing the depths of geology, *Ann. Rev. Earth Planet. Sci., 24*, 385–432, 1996.

Schutt, D., E. D. Humphreys and K. Dueker, Anisotropy of the Yellowstone Hot Spot wake, eastern Snake River Plain, Idaho, *PAGEOPH, 151* 443-462, 1998.

Vauchez, A. and A. Nicolas, Mountain building; strike-parallel motion and mantle anisotropy, *Tectonophysics*, *185*, 183–201, 1991.

Vauchez A. and G. Barruol, Shear-wave splitting in the Appalachians and Pyrenees: importance of the inherited tectonic fabric of the lithosphere, *Phys. Earth Planet. Inter., 95*, 127–138, 1996.

Vinnik, L. P., L.I. Makeyeva, A. Milev, and A. Yu. Usenko, Global patterns of azimuthal anisotropy and deformations in the continental mantle, *Geophys. J. Int.*, *111*, 433–447, 1992.

Vinnik L. P., V. G. Krishna, R. Kind, P. Bormann and

K. Stammler, Shear-wave splitting in the records of the German Regional Seismic Network, *Geophys. Res. Lett., 21*, 457-460. 1994.

Vinnik, L. P , R. W. E. Green and L. O. Nicolaysen, Recent deformations of the deep continental root beneath Southern Africa. *Nature*, *375*, 50-52, 1995.

Vinnik, L. P. and J.-P. Montagner, Shear-wave splitting in the mantle Ps phases, *Geophys. Res. Lett., 23*, 2449–2452, 1996.

Wessel, P. & W. H. F. Smith, 1991. Free software helps map and display data, *Eos Trans. AGU, 72*, 441.

Wolfe, C. J. and P. G. Silver, Seismic anisotropy of oceanic upper mantle; shear-wave splitting methodologies and observations, *J. Geophys. Res., 103*, 749 - 771, 1998.

Wolfe, C. J. and S. C. Solomon, Shear-wave splitting and implications for mantle flow beneath the MELT region of the East Pacific Rise, *Science, 280*, 1230-1232, 1998.

Zhang, S. and S. Karato, Lattice preferred orientation of olivine aggregates deformed in simple shear, *Nature, 375*, 774–777, 1995.

Zonenshain, L. P., V. G. Korinevsky, V. G. Kazmin, D. M. Pechersky, V. V. Khain, and V. V. Matveenkov, Plate tectonic model of the South Urals development, *Tectonophysics, 109*, 95–135, 1984.

V. Levin, J. Park, Dept. of Geology and Geophysics, Box 208109, Yale University, New Haven, CT 06520 (email: vadim@hess.geology.yale.edu; park@hess.geology.yale.edu)

W. Menke, LDEO, Palisades, NY email: menke@ldeo.columbia.edu

; revised ; accepted .

This preprint was prepared with AGU's LaTeX macros v4. File ApUr.rev1-pp formatted March 12, 1999.

With the extension package 'AGU^{++}', version 1.2 from 1995/01/12

Table 1. Anisotropic structure (hexagonal symmetry) consistent with shear-wave splitting observations at HRV. "Depth" indicates the bottom of each layer. The parameters B and E scale peak-to-peak variations of compressional and shear velocity, respectively, each with $\cos 2\eta$ azimuthal dependence [*Park*, 1996]. The angles θ and ϕ define the tilt (from vertical) and strike (CW from N) of the axis of symmetry within each anisotropic layer.

depth (km)	Vp, km/s	Vs, km/s	ρ (g/cm^3)	B (% of Vp)	E (% of Vs)	θ (°)	ϕ (°)
35	6.00	3.60	2.5	0	0	-	-
135	8.00	4.60	3.1	3	3	75	100
235	8.00	4.60	3.1	4	4	130	50
∞	8.20	4.7	3.3	0	0	-	-

Table 2. Anisotropic structure (orthorhombic symmetry) consistent with shear wave splitting observations at HRV. Velocity values in anisotropic layers are the isotropic averages of respective elastic tensors. The anisotropic medium is modeled as 30% orthorhombic olivine and 70% isotropic olivine, a mixture that is $\sim$ 6% anisotropic. The angles θ and ϕ define the tilt (from vertical) and azimuth (CW from N) of the symmetry axes (fast, intermediate, slow) within each anisotropic layer.

depth (km)	Vp, km/s	Vs, km/s	ρ (g/cm^3)	θ_f (°)	ϕ_f (°)	θ_i (°)	ϕ_i (°)	θ_s (°)	ϕ_s (°)
40	6.8	3.9	2.85	-	-	-	-	-	
100	8.3	4.8	3.3	89	115	80	25	10	210
190	8.3	4.8	3.3	90	53	67	323	23	143
∞	8.3	4.8	3.3	-	-	-	-	-	

Table 3. Anisotropic structure (hexagonal symmetry) consistent with P-coda receiver functions [*Levin and Park*, 1997a] and shear-wave splitting observations at ARU. Depth indicates the bottom of each layer. The parameters B and E scale peak-to-peak variations of compressional and shear velocity, respectively, each with $\cos 2\eta$ azimuthal dependence [*Park*, 1996]. The angles θ and ϕ define the tilt (from vertical) and strike (CW from N) of the axis of symmetry within each anisotropic layer.

depth (km)	Vp, km/s	Vs, km/s	ρ (g/cm^3)	B (% of Vp)	E (% of Vs)	θ (°)	ϕ (°)
1	5.00	2.95	2.1	-15	0	45	345
20	6.40	3.70	2.3	0	0	-	-
23	5.8	3.30	2.3	0	0	-	-
33	6.60	3.80	2.6	0	0	-	-
42	7.60	4.40	3.0	-15	-15	65	230
100	8.00	4.60	3.2	6	6	80	50
240	8.00	4.60	3.2	4	4	130	90
∞	8.20	3.3	4.7	0	0	-	-

Figure 1. Shear-wave fast direction and delay for SKS waves received at a hypothetical station from a variety of directions and apparent velocities (in km/s). Data are shown as a bar centered on the nominal back azimuth and apparent velocity, with the bar's orientation parallel to the azimuth of the the fast direction, and its length proportional to the delay. Near-zero delays are plotted with open circles. (Left) For an earth model with a single hexagonally-anisotropic layer with horizontal symmetry axis overlying an isotropic halfspace; (Right) for a model in which the symmetry axis plunges 45 degrees. Note that the splitting parameters vary most slowly in the horizontal case.

Figure 2. Synthetic SKS phases for two earth models. (Right) Two 50 km hexagonally-anisotropic layers overlying an isotropic halfspace. The symmetry axis is horizontal in both layers, and has an azimuth of N30E in the top layer and N60E in the bottom layer. (Left) One 100 km anisotropic layer overlying an isotropic halfspace. The anisotropic tensor is the arithmetic mean of the tensors in the two-layer case. Radial (top row) and transverse (second row) horizontal component synthetic seismograms (bold) are computed by convolving the impulse response

functions (solid) with a pulse that has a bandwidth similar to typical SKS phases. This SKS pulse ($N270°E$, 20 km/s) (third row) is reconstructed using apparent splitting parameters computed by the cross-correlation method. Note that the two layer case has the larger error (bottom row).

Figure 3. Apparent splitting parameters for SKS waves received at a hypothetical station. (Right) For an earth model with two 50 km hexagonally-anisotropic layers overlying an isotropic halfspace. The symmetry axis is horizontal in both layers, an has an azimuth of N30E in the top layer and N60E in the bottom layer. (Left) For an earth model with one 100 km anisotropic layer overlying an isotropic halfspace. The anisotropic tensor is the arithmetic mean of the tensors in the two-layer case. Splitting parameters are computed by the cross-correlation method from synthetic SKS phases. Note that the two layer case has the more complex pattern.

Figure 4. Influence of the filtering applied to the synthetic waveforms on the apparent splitting parameters. Waveforms are simulated in a 2-layer model developed for station HRV (see Table 2). Apparent splitting parameters measured from waveforms with an upper spectral limits of 0.45Hz (bold), 0.35Hz (solid) and 0.15Hz (dotted) are shown, with a lower limit of 0.05Hz common for all. For all cases tested the estimate of the apparent fast direction tends to vary greatly when the delay is the smallest. The lowest bandpass (0.15Hz) gives most unstable results throughout.

Figure 5. Map of NE Appalachian region, with "average" parameters of seismic anisotropy plotted at points where they were constrained by various workers. Arrow azimuths correspond to the fast directions determined for the particular site, and are scaled with estimated delay. The compilation is extracted from the "Anisotropy Resource Page" maintained by Derek Schutt (*http : //darkwing.uoregon.edu/ ∼ schuttd/aniso_source.html*). Individual values are from *Silver and Chan*, [1991]; *Bostock and Cassidy*, [1995]; *Barruol et al.*, [1997] and *Fouch et al.*, [1999].

Figure 6. Histograms of single seismogram splitting parameter errors for HRV data. *(top)* One σ error in delay time. *(bottom)* One σ error in fast direction azimuth.

Figure 7. Map of NE Appalachian region showing shear-wave splitting data for two earthquakes with different propagation directions (large one-sided arrows) observed in 1995. Splitting azimuth and delay are shown at each station as two-sided arrows aligned with the fast direction and scaled with delay. Symbols are color-coded by event, black for one and white for the other. Note that splitting directions for the two events is quite different, yet is fairly consistent across the region for each event.

Figure 8. Shear-wave splitting data for PAL and HRV. Note that the pattern is similar for the two stations, but varies rapidly with back azimuth. Splitting directions for S_{diff} phases (two data points from back azimuth 335° for HRV, three data points from back azimuths $257-263°$ for PAL) closely match those obtained for SKS phases from the same events. Thus contamination of the S_{diff} signal by the D'' anisotropy [*Garnero and Lay*, 1997] does not seem to occur along these particular paths. S phases from South American earthquakes with hypocenters deeper then 500 km are included to provide coverage from the south.

Figure 9. Shear-wave splitting data for the subset of PAL and HRV data that fall within 3° of each other, superimposed on one another (black, HRV; grey, PAL). Note overall similarity of pattern.

Figure 10. Histogram of the angle between pairs of fast azimuth measurements for the station HRV. The distribution is bimodal, suggesting that two distinct fast azimuths are present.

Figure 11. SKS waves observed at HRV for 4 different backaziumths, A) SSE, B) WNW, C) NNW and D) NNE. (Left) Observed radial (top row) and transverse (3rd row) horizontal component seismograms. The significant energy observed on the transverse component is an effect of the seismic anisotropy. Corrected radial (2nd row) and transverse (bottom row) component seismograms, where the effect of propagation through the anisotropic medium has been removed. (Right) Particle motion diagrams *(top)* before and *(bottom)* after correction. Note that the energy on the transverse component has been greatly reduced, and the particle motion made significantly more linear, indicating that the splitting parameters have been correctly calculated.

Figure 12. Anisotropic tensor orientations for (top) 1 layer and (bottom) two layer models for HRV. The fast, intermediate and slow axes are denoted F, I and S, respectively. Top and Bottom layers are denoted T and B, respectively.

Figure 13. (Left) Shear-wave splitting patterns for best-fitting one-layer (top) and two-layer (bottom) HRV

models. (Right) Observed (gray) and predicted (black) shear-wave splitting parameters.

Figure 14. Observed and predicted variation of the apparent fast direction at HRV. Observations are shown by triangles with error bars. A subset of "robust" data points (circled) was chosen so that $\sigma_\tau < \tau/3$. Clearly, "robust" and "poor" data points follow the same pattern. Crosses show values of fast direction reported for HRV by *Barruol et al.* [1997] (as given in electronic supplement table 2). Thick lines show patterns predicted by our orthorhombic (solid) and hexagonal (dotted) models, thin lines show predictions for equivalent 2-layer splitting operators [*Silver and Savage*, 1994]. While all models capture the periodicity of the pattern, the spread of values and the deviations from the 2π pattern are not matched by the splitting operator predictions.

Figure 15. A schematic representation of the model for seismic anisotropy distribution under HRV.

Figure 16. Regional setting of GSN station ARU (open triangle) and the geometry of inferred anisotropy in the lithosphere. Grey lines - topography contours at 330 and 560 m. Wide grey line: the main Uralian Fault Zone. Open arrow: the symmetry axis of lower-crustal anisotropy. Grey bars: inferred fast axes of anisotropy for the two layers in the mantle.

Figure 17. Shear-wave splitting data for ARU (Arti, Russia). See Figure 1 for plotting conventions.

Figure 18. (Left) Shear-wave splitting patterns for best-fitting one-layer (top) and three-layer (bottom) ARU models. (Right) Observed (gray) and predicted (black) shear-wave splitting parameters.

Figure 19. Symmetry axes of best-fitting hexagonal tensors for ARU. Crust and mantle are labeled C and M, respectively. Top layer and bottom layers in the mantle are labeled T and B, respectively. In the bottom layer of anisotropy the symmetry axis plunges 40° to the east, which is equivalent to an upward tilt of 40° to the west.

Figure 20. A schematic representation of the model for seismic anisotropy distribution under ARU (marked by a flag), with the lowermost crust anisotropy (dark arrow marked "slow") from the model of *Levin and Park*, [1997a].