JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 105, NO. B8, PAGES 19,029–19,042, AUGUST 10, 2000

No regional anisotropic domains in the northeastern U.S. Appalachians

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Abstract. A fabric "frozen" within the continental lithosphere should lead to "regional anisotropic domains" with close correlation between tectonics, seismic anisotropy, and shear wave travel time delays. Alternatively, seismic anisotropy could be maintained by active deformation in the sub-lithospheric mantle. This scenario would predict broad spatial consistency in shear wave splitting and weak correlation between the splitting, surface tectonics, and travel time delays. A coherent pattern of shear wave splitting is observed in the northeastern United States, covering large parts of New York and New England, spanning the Appalachian Orogen and areas underlain by the Grenvillian basement. The direction of fast shear wave propagation, as measured from core-refracted SKS, $SKKS$, and PKS phases, varies systematically with event back azimuth at all sites examined, and is fit well by two-layers of anisotropy with subhorizontal symmetry axes. Relative travel time delays of shear waves that sample the region vary over 100 km length scale, and correlate with surface geology. Tomographic images suggest lateral shear velocity variations ~3%, including a slow anomaly beneath the Grenvillian basement exposed in the Adirondack Mountains. There is little correlation between this horizontally rough seismic velocity and the horizontally smooth anisotropic model consistent with shear wave splitting. We therefore conclude that in the northeastern US the concept of "regional anisotropic domains" (i.e. distinct regions within the lithosphere characterized by coherent anisotropic properties reflective of present or past deformation) does not apply.

1. Introduction

Olivine, the major mineralogical species in the upper mantle of the Earth, is highly anisotropic [*Kumazawa and Anderson*, 1969]. If a significant fraction of the olivine grains in a volume within the mantle have their crystallographic axes aligned parallel to one another, as can happen through the effect of strain [*Zhang and Karato*, 1995], that volume can take on a net seismic anisotropy. Two neighboring volumes with different amounts of alignment or different alignment orientations will possess different seismic properties. There is ample evidence from the study of the birefringence (splitting) of the two polarizations of teleseismic shear phases (e.g., SKS) that most of the upper mantle is in fact anisotropic [e.g., *Vinnik et al.*, 1992; *Silver*, 1996]. A worldwide summary by *Silver* [1996] indicates that a typical SKS wave is split by 0.5-1.5 s. This translates into 50–150 km of anisotropic mantle beneath a typical point on the Earth's surface, presuming 5% shear anisotropy, on the high end of mantle rocks exposed in ophiolites and kimberlite nodules [*Mainprice and Silver*, 1993].

The origin of anisotropic fabric within continental mantle is controversial. *Vinnik et al.* [1992] argued for an origin related to the Earth's current stress field, via a "dynamic" fabric imposed within the upper mantle below the continents. In this view, indicators of seismic anisotropy should be fairly coherent over large areas, and generally independent of the features exposed on the surface. *Silver* [1996], citing the general agreement between mantle fabric directions and

Paper number 2000JB900123.
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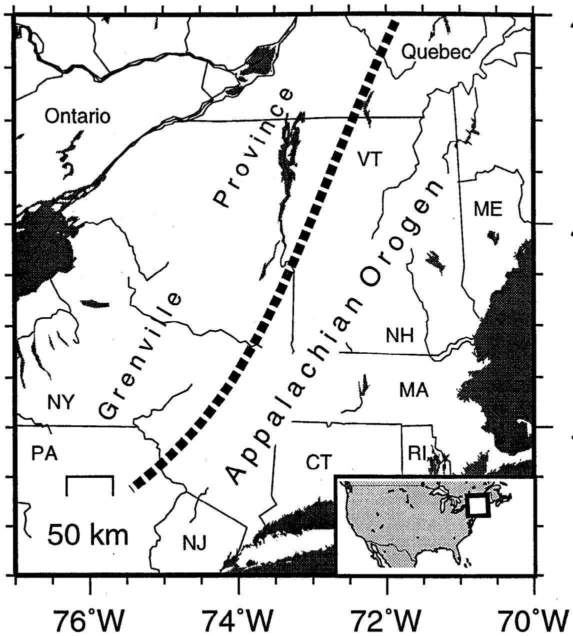

Figure 1. Map of the study area. Wide dashed line shows the transition from Grenville Orogen to the Appalachian Orogen, with the Adirondack Mountains shown as a shaded area.

surface geology, argued that the anisotropy is "frozen" into the continental lithosphere. This model provides a mechanism for the production of small (100–200 km) anisotropic domains, regions within the mantle that have coherent fabric and display similar anisotropic properties. It envisages large regions with uniform mantle fabric forming in the process of continental lithosphere creation, getting torn up by later tectonic events, later to be reoriented and reassembled into stable cratons. In a wide variety of environments, however, both frozen anisotropy and dynamic anisotropy appear to contribute to the observed splitting signal [*Savage*, 1999; *Wolfe and Solomon*, 1998].

Levin et al. [1996] argued that a typical velocity heterogeneity of about 2.5% (i.e., teleseismic P wave fluctuations of about 0.3 s) would be expected from randomly oriented anisotropic domains, if these domains have anisotropy sufficient to produce the 1-s global median splitting times reported by *Silver* [1996]. Shear wave splitting demonstrates that the mantle is anisotropic, and anisotropy can be shown to cause travel time heterogeneity as large as that implied by mantle tomography. We might ask whether it can account for most or all of the apparent velocity heterogeneity observed in older, stable continental regions where lateral variation in temperature is unlikely.

The northeastern United States presents an excellent testing ground for the above hypothesis. The region borders a stable passive margin, with most recent tectonism associated with the passage of the Monteregian hotspot at ~100 Ma [*Sleep*, 1990]. On the other hand, the tectonic history of the region spans two Wilson cycles. Remnants of two collisional orogens (Grenvillian and Appalachian) compose most of the area (Figure 1). Several accreted terranes have been identified within the younger Appalachians [*Zen*, 1983; *Taylor*, 1989]. The more ancient Grenvillian Orogen also has internal variations [*Moore*, 1986; *Rivers et al.*, 1989]. If the "anisotropic domain" paradigm is universally applicable, it should be clearly manifested here.

Seismic velocities in the eastern North American lithosphere and upper mantle have been studied using teleseismic travel time delays of short-period P waves [*Taylor and Toksoz,* 1979; *Levin et al.*, 1995], and using surface wave travel time delays [*Van der Lee and Nolet*, 1997; *Li et al.*, 1999]. Seismic anisotropy in the upper mantle has been identified in studies of shear wave splitting [*Silver and Chan*, 1991; *Vinnik et al.*, 1992, *Levin et al.*, 1996, 1999; *Barruol et al*, 1997; *Fouch et al.*, 2000]. The interpretation of the observed splitting parameters varies. *Levin et al.* [1996] and *Barruol et al.* [1997a] correlated a sharp lateral variation of splitting with major tectonic features to argue for the "frozen fabric" model. *Fouch et al.* [2000] argued that a large

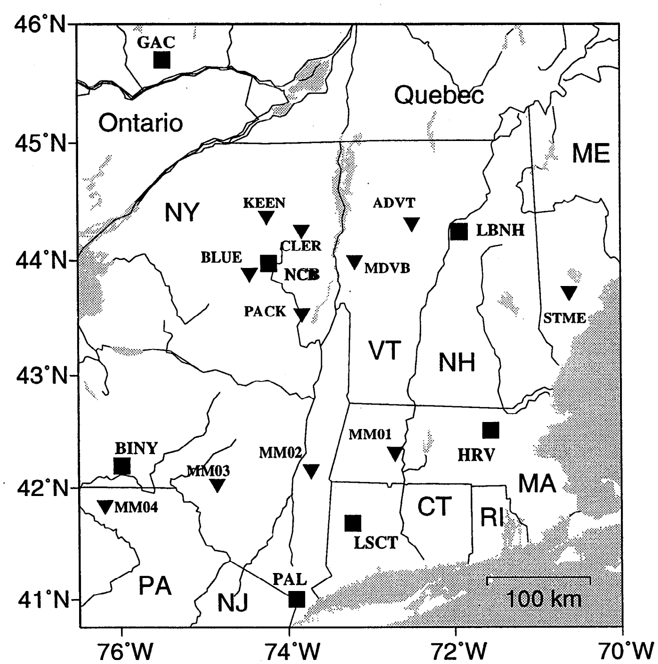

Figure 2. Seismic stations used in this study. Permanent installations (squares) belong to U.S. and Canadian national networks, Global Seismic Network (GSN) and Lamont-Doherty Earth Observatory (LDEO). Temporary deployments include Missouri to Massachusetts (MOMA), and Adirondack Broad-Band Array (ABBA) deployments, and stations operated by the authors (see Table 3). The network configuration shown was deployed during the spring and summer of 1995.

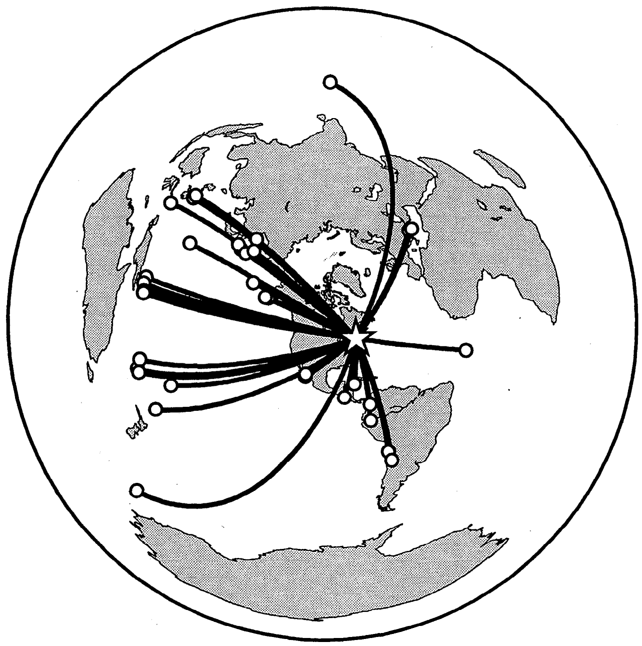

Figure 3. Locations of earthquakes recorded by the network. Events arriving from the west dominate the data set.

portion of the lateral variability in splitting parameters may be explained by a complex flow pattern in the mantle and favored the "dynamic fabric" model.

A third option became apparent when *Levin et al.*, 1999] demonstrated that a large sample of SKS waves observed at the Global Seismic N etwork (GSN) station HRV (Weston, Massachusetts) displayed back azimuthal variation consistent with vertical heterogeneity in anisotropy. Multilayered anisotropy is difficult to constrain with sparse splitting observations and can easily be misinterpreted as lateral variation if splitting estimates for geographically separated stations are made from earthquakes at widely separated back azimuths. However, multilayered anisotropy may be more difficult to place in a "fossil" or "dynamic" tectonic context.

To resolve these issues, we examine properties of teleseismic shear waves observed synoptically by a network of stations in the northeastern United States (Figure 2). We measure shear wave splitting of core-refracted phases like SKS, and determine relative travel time delays of shear waves. Our main finding is that given a sufficient volume of data, the pattern of anisotropy is more laterally homogeneous than was previously thought. We find significant back azimuthal variation in shear wave splitting parameters at all sites. This variation is similar among stations and is approximated well by the two-layer anisotropic model derived by *Levin et al.*, 1999] for station HRV. Moreover, there is no obvious correlation between the splitting parameters (indicative of anisotropy) and the relative travel time delays (indicative of velocity variation) of teleseismic shear waves.

In the following sections we describe our observations and a two-layer model that fits them, and discuss potential mechanisms that could lead to the formation of such a structure in this stable continental region.

2. Observations

During the spring and summer of 1995 three independent broadband networks operated in the northeastern United States, complementing the existing permanent observatories (Figure 2). Earthquakes recorded by this

Table 1. Earthquakes Used in the Study

Event	Latitude, deg	Longitude, deg	Depth, km
9503141733	54.80	-161.40	33
9504072206*	-15.20	-173.60	33
9504172328	45.90	151.30	33
9504210517*	12.20	126.30	33
9504230255	51.33	179.71	17
9504281630	44.07	148.00	29
9505020606	-3.80	-76.90	120
9505050353*	12.60	125.20	33
9505130847	40.15	21.70	14
9505162012*	-22.90	169.70	33
9505180006	-0.89	-22.00	12
9505271303	52.63	142.83	11
9506141111	12.20	-88.35	39
9506150015	38.40	22.27	14
9506211528	-61.62	154.71	10
9506240658*	-3.98	153.94	386
9506250210	-3.28	150.37	45
9506271009	18.85	-81.73	10
9506290745	48.78	154.46	62
9506291224*	-19.46	169.24	144
9506301158	24.62	-110.26	10
9507031950*	-29.20	-177.61	33
9507081715	53.65	-163.55	33
9507121546*	-23.24	170.82	33
9507262342*	2.56	127.69	66
9507270551*	-12.58	79.24	10
9508020014	-23.15	-70.58	33
9508021105	-23.10	-70.41	33
9508030157	-23.13	-70.60	33
9508030818	-28.35	-69.20	104
9508041331	52.87	152.90	529
9508140437*	-4.83	151.51	126
9508161027*	-5.81	154.21	16
9508161624	-5.42	153.76	21
9508162310	-5.78	154.26	74
9508192143	5.10	-75.69	125
9508230706*	18.86	145.19	596
9508281046	26.16	-110.35	10

Locations determined by National Earthquake Information Center (NEIC).

*Events used in the study of shear wave splitting.

Table 2. Seismic Stations Used in the Study

Station Name	Latitude, °N	Longitude, °W	Operator
ADVT	44.32	72.49	Levin and Menke
BINY	42.19	75.99	USNSN
BLUE	43.89	74.45	ABBA
CLER	44.38	74.25	ABBA
GAC	45.70	75.48	CNSN
HRV	42.50	71.56	GSN
KEEN	44.26	73.82	ABBA
LBNH	44.24	71.93	USNSN
LSCT	41.68	73.22	USNSN
MDVB	43.99	73.18	Levin and Menke
MM01	42.32	72.71	MOMA
MM02	42.17	73.72	MOMA
MM03	42.04	74.85	MOMA
MM04	41.85	76.19	MOMA
NCB	43.97	74.22	LDEO
PACK	43.54	73.82	ABBA
PAL	41.00	73.91	IRIS and LDEO
STME	43.72	70.61	Levin and Menke

In addition to permanent stations operated in the region by national and international networks we used some nodes of portable broadband networks, and stations we deployed ourselves to complement the coverage. Abbreviations are as follows: USNSN, U.S. National Seismic Network; ABBA, Adirondack Broad Band Array; CNSN, Canadian National Seismic Network; GSN, Global Seismic Network; MOMA, Missouri to Massachusetts Array; LDEO, Lamont-Doherty Earth Observatory; and IRIS, Incorporated Research Institutions for Seismology. (See http://www.iris.washington.edu/PASSCAL/EasternUS.htm for detailed descriptions.)

composite network are shown in Figure 3 and are also listed in Table 1. Stations are listed in Table 2. The distribution of earthquakes is heavily biased toward the Pacific region, with only a handful of sources in other quadrants. The composite network contained a variety of seismic sensors. In order to homogenize the data set, we corrected observed waveforms for the respective instrument responses, filtered resulting velocity time series between 0.01 and 0.2 Hz, and resampled them at 10 samples per second. Seismic phases of interest were first identified by visual inspection of record sections, with rough (within a few seconds) time alignment done by picking a characteristic part of the broadband waveform. The time window selected for the subsequent analysis varied between 25 and 75 s, depending on the length and clarity of the phase.

2.1. Shear Wave Splitting

Splitting was estimated using cross correlation of the horizontal components of motion [*Levin et al.*, 1999]. This method assumes that propagation through the anisotropic medium leads to the splitting of an originally rectilinear S pulse into two orthogonally polarized time-shifted versions of it. It therefore seeks a rotation ϕ and a delay τ that would result in an optimally similar particle motion on two components, as defined by maximal cross correlation. We use core-refracted phases (SKS, $SKKS$, and PKS) which contain information about anisotropy only along the path from the core-mantle boundary to the surface [*Vinnik et al.*, 1984]. Figure 4 shows waveforms for two such phases that arrive from different back azimuths, and maps with estimated splitting parameters. Fast axis estimates from the same phase are similar at the majority of sites. Fast axis estimates from two different phases at a single site often differ significantly. In contrast, estimates of the splitting delay tend to vary more across the composite network for single phases and between the two events. Figure 5 shows all shear wave splitting observations. Stations with observations from a variety of directions exhibit a strong dependence of splitting parameters on the back azimuth. This dependence does not correlate with the choice of the seismic phase (e.g., SKS versus $SKKS$) in our data set, although frequency content and incidence angles of individual phases undoubtedly influence our measurements. Back azimuthal dependence is not apparent at stations where data are available from a limited range (STME, NCB, KEEN). However, when combined with observations from other sites (Figure 8), their splitting parameters fall onto the same trend.

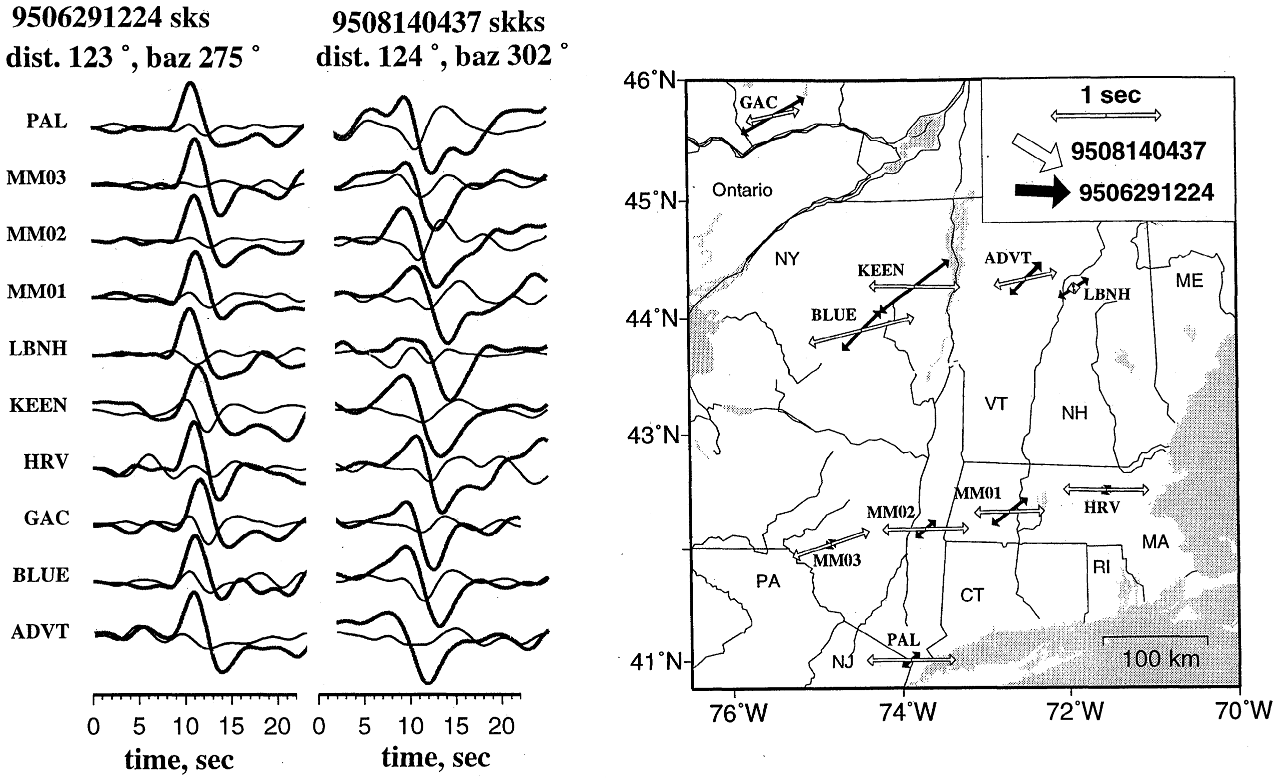

Figure 4. (a) Two core-refracted shear phases observed by the network. Waveforms are velocity time series corrected for instrument response and band-limited between 0.01 and 0.2 Hz. Bold lines show radial component; thin lines show the transverse. (b) Map of the region showing shear wave splitting parameters detemined for the two phases. Splitting azimuth and delay are shown at each station as arrows aligned with fast direction ϕ and scaled with delay τ. Splitting arrows, as well as phase vectors in the upper left, are coded by event, solid arrows for one and open arrows for the other. Note that the splitting direction for the two events is quite different, yet is fairly consistent across the region for each event.

2.2. Relative Travel Time Delays

Relative travel time delays were determined for all phases used in shear wave splitting analyses, and also for all clear S phases. The pulse shape of a typical shear phase does not vary significantly over the region, allowing us to estimate relative travel-time delays using cross correlation. For core-refracted phases like SKS we used the radial components of motion. Experiments with other rotations (e.g., fast directions for the particular phase) showed no significant difference in estimated delays. The polarization of direct S and S_{diff} phases varies with the earthquake source in addition to path effects. For these phases we chose either the radial or transverse component, depending on the clarity of the signal. In cases where signal was equally clear on both components we tested both, and found close similarity in estimated delays. Most earthquakes in our data set were recorded by a subset of the full composite network. We took a number of steps, described below, to compensate for the bias attributable to the variations in network configuration.

We determined travel time delays using windowed time series that had already been aligned roughly. From the group of observations we constructed an average waveform. Using cross correlation, we aligned the records of a phase relative to one of the observations in the group, and stacked and normalized them to produce an average pulse. We repeated this operation as a cross-check, using an observation from a different station as a base. All average pulses produced in this manner were aligned and stacked once more. We related the average waveform to the geometric center of the subset of stations observing the phase, and assigned an average starting time to it. Constructed in this manner, the average waveform should approximate the true pulse shape, as the varying distortions due to local conditions at individual stations (noise, near-surface structure, topography) should be suppressed. Pulse distortions that might be common to all stations in the network would not affect differential travel time delays. We computed time shifts of individual phases relative to this average waveform, and corrected them for the moveout pre-

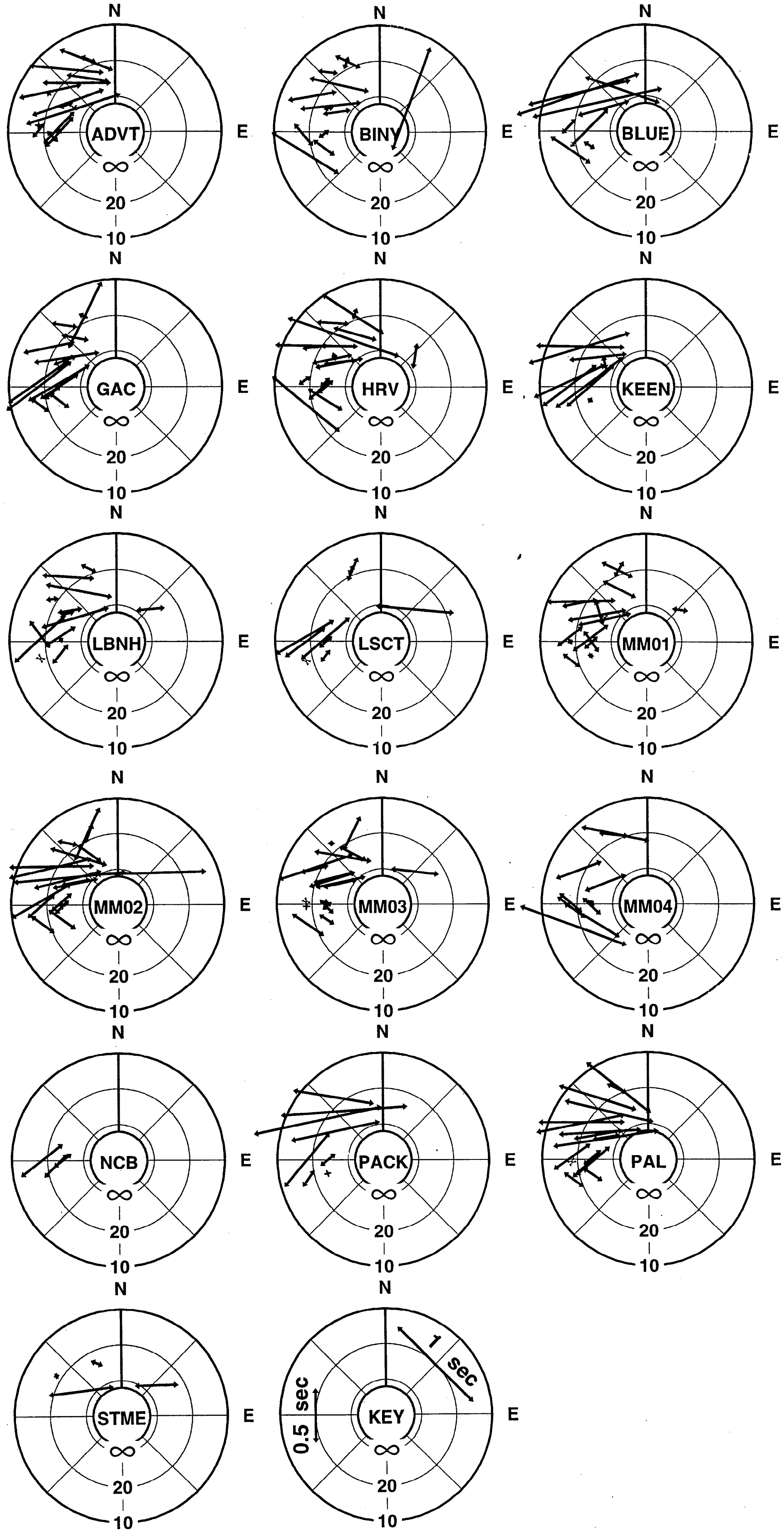

Figure 5. Splitting parameters obtained for all stations. Observations are shown as arrows aligned with the fast direction ϕ and scaled with delay τ, plotted as a function of back azimuth and horizontal phase velocity of the appropriate phase ($SKS, SKKS, PKS$) as predicted by the "iasp91" model. Phases with steeper incoming ray paths plot closer to the center of the diagrams. At all stations, significant differences are seen between splitting parameters obtained from different directions.

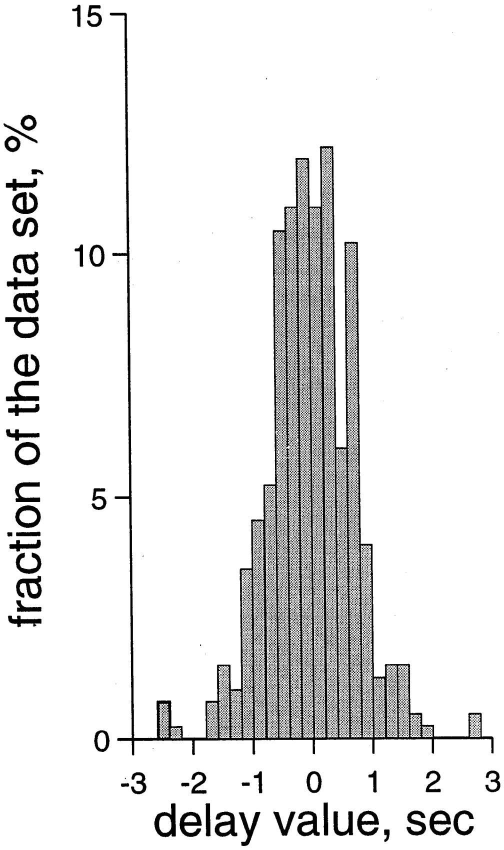

Figure 6. A histogram of relative travel time delays determined for the network. The majority of delays do not exceed 1.5 s.

dicted by the *iasp*91 model with source-receiver distance. At this stage most groups of delays contained a linear trend with epicentral distance, implying a deviation from the one-dimensional (1-D) *iasp*91 velocity structure along the source-receiver path. We estimated this trend by fitting a straight line to the relative delays and removed it. Residual delays were generally less than 1.5 s in magnitude and were normally distributed (Figure 6). Most stations in the Adirondack Mountains (BLUE, PACK, NCB, KEEN) have slow delays associated with them, and stations GAC, PAL, and LSCT are almost always fast (Figure 7). Stations ADVT, HRV, and MM01 show strong azimuthal dependence of delays.

3. Results and Interpretation

3.1. Variations in Shear Wave Splitting Parameters

Back azimuthal variability of shear wave splitting parameters occurs at all sites in the composite network that have a sufficient number of observations. When fast directions for all stations are graphed as a function of back azimuth (Figure 8), an overall similarity of the pattern is revealed, which is matched well by the two-layer model of anisotropy under HRV derived by *Levin et al.*, [1999] (see Figure 9 and Table 3). In back azimuthal range 260° - 290°, two branches of the data pattern overlap. This overlap results from modest regional variations in the splitting pattern, which are clearly discernible when the highest quality data is graphed (Figure 10). The break in the pattern occurs at 260° for the stations close to the Atlantic coast (PAL, LSCT, MM01, HRV), is at 290° for the westernmost stations (BINY, MM03, MM04), and is not seen at all (or is very much shifted) for the stations over the Grenville province (PACK, BLUE, KEEN, GAC) and station LBNH. Such "drift" of the break in the pattern can be explained by small perturbations to the HRV model, for example ±10 km fluctuations in the thickness of either layer (Figure 11). Small (~1%) regional trends in anisotropy strength within either layer could also cause these variations in the splitting pattern. Such small perturbations of the HRV model would not alter the travel times of teleseismic shear waves enough to match the magnitude of relative delays observed in the region.

The strong variation of splitting parameters with back azimuth can easily be mistaken for lateral heterogeneity, especially when different sets of events are used to estimate splitting at different stations. This effect may account for the early interpretation that the anisotropy in the northeastern North America has strong lateral variation. The difference in anisotropy between neighboring stations can be overestimated even when a common set of events is analyzed, if the event set spans too small a range of back azimuths. A small rotation between azimuthally varying patterns could be mistaken for a large difference between the overall patterns. In light of this study, we conclude that *Levin et al.* [1996] overestimated the heterogeneity between the Adirondack and New Hampshire regions.

3.2. Variation in Seismic Velocity

Traveltime residuals indicate that shear velocity fluctuates locally over the study region. Stations separated by 100 km or less (e.g., MM01 and PAL, ADVT and LBNH) display strong differences in their relative delay patterns (Figure 7). The distribution of earthquakes in our data set is fairly uneven, and the resulting sampling under the composite network by ray paths is not optimal for tomographic imaging. Nevertheless, the projection of delays onto the ray set using a simple model provides useful constraints on the scale length and depth distribution of the heterogeneity responsible for the delays. We approximated the volume under the region with a rectangular box divided into horizontal layers 100 km thick. Each layer was divided into a number of boxes. Using a 1-D velocity model based on *iasp*91, we traced S rays through this model. Hit counts in individual boxes and resolution tests with simple shapes indicate that the layer between 100 and 200 km under the central part of the network is sampled sufficiently well to resolve velocity features of scale length 100-200 km. Figure 12 shows the S velocity distribution in the central part of this layer. The resolution of features outside the region immediately under the network was poor. The exact shapes of the anomalies depend strongly on the number of boxes in the layer and therefore are not well constrained. Nevertheless, the general locations of anomalies and an overall $\pm 3\%$ small-scale variation in shear velocity persist with different choices of parameterization. The slow feature under the Adirondack Mountains dominates the image and is the most robust element of the inversion.

Overall, there is little correlation between the splitting parameters estimated from the core-refracted shear phases and apparent shear velocity variations under the region. While anisotropy indicators depend on back azimuth at all sites, the relative travel time delays exhibit significant azimuthal variability at only three sites (ADVT, HRV, and MM01). Only a slight variation of the two-layer anisotropic model is needed to accommodate regional variations in the azimuthal pattern of fast directions, but such modest variability will not predict the velocity perturbations (Figure 12) required to generate the observed delays.

4. Discussion

The complicated nature of seismic anisotropy in the northeastern United States has been noted in a number of previous papers. *Levin et al.* [1996] reported lateral variations in observed splitting parameters of individual phases that appeared to correlate with tectonic units of the region. Working with averaged splitting parameters, *Barruol et al.* [1997a] suggested that throughout the eastern North America (a region much broader than this study) there is a good fit between surface geology

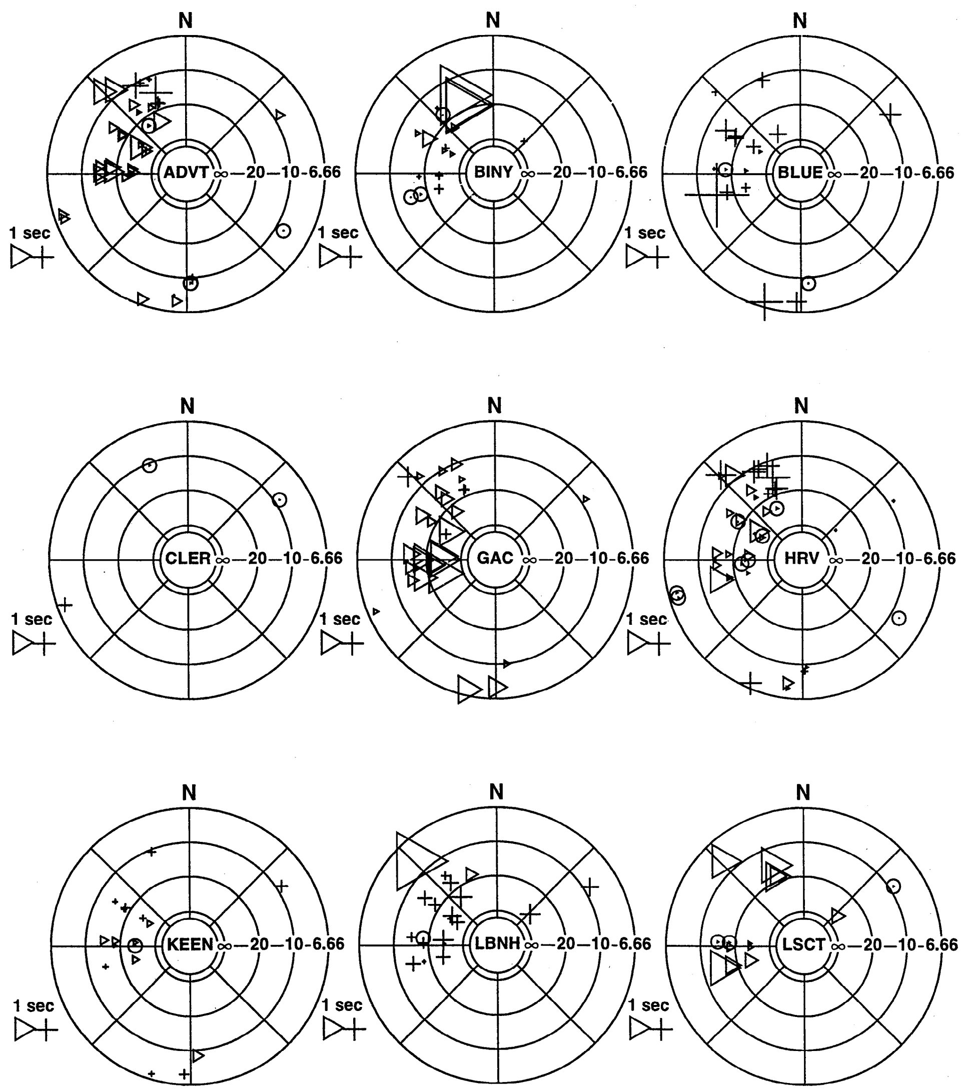

Figure 7. Relative delays determined for the stations of the network. Positive delays (pluses) and negative delays (triangles) are plotted as a function of back azimuth and horizontal phase velocity of the appropriate phase (S, SKS, etc.) as predicted by the "iasp91" model. Phases with steeper incoming ray paths plot closer to the center of the diagram. Open circles denote delays under 0.1 s.

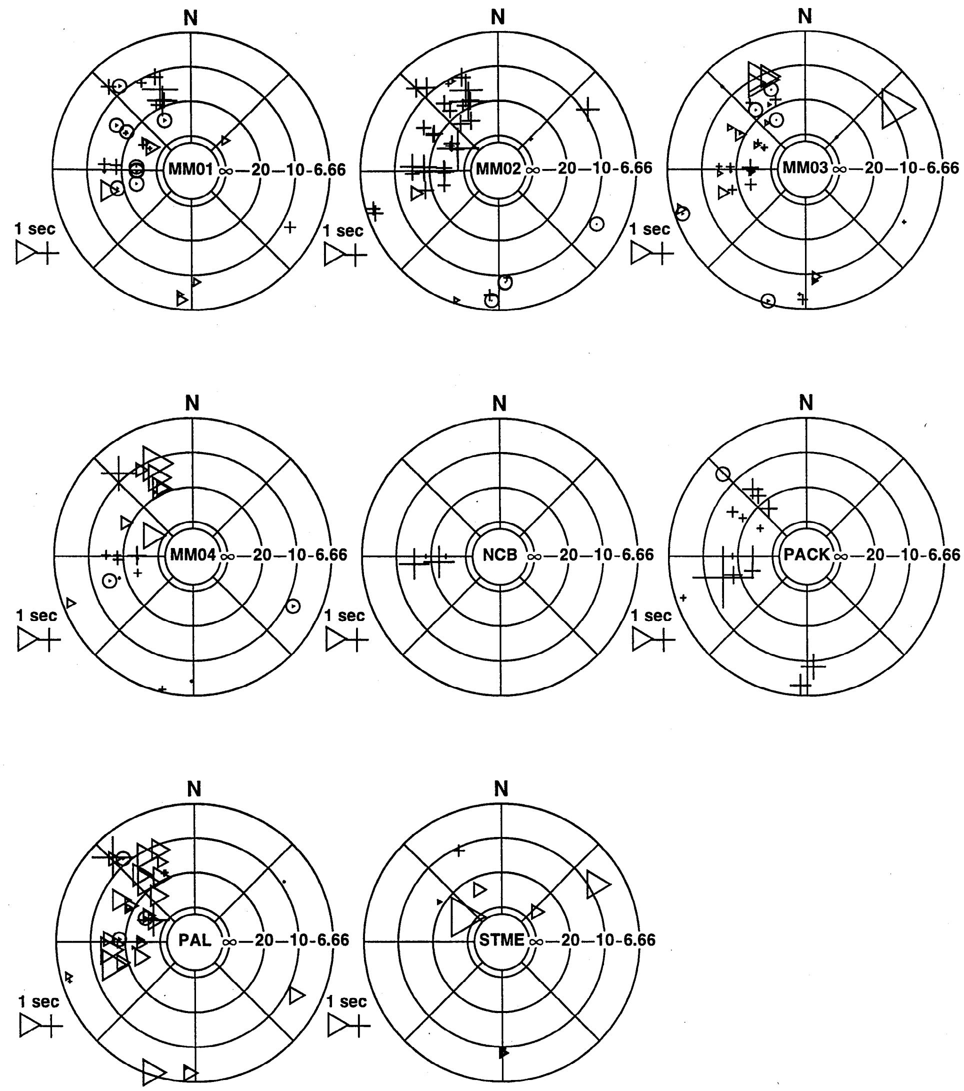

Figure 7. (continued)

and fast direction ϕ. *Barruol et al.* [1997a] described our study region as "anomalous" because the averaged fast axis orientations they obtained were near normal to the strike of the local tectonic features. More recently, *Fouch et al.* [2000] showed that averaged splitting parameters in a broad region of eastern North America may alternatively be explained by the mantle flow pattern around the keel of the North American craton. In their results our study region stands out as an area where a single-layer splitting model is least successful. Further observations will be needed to determine how our two-layer model joins with the rest of eastern North America, where other studies suggest that one layer suffices.

In this paper we examine splitting parameters of individual phases, not station averages. A comparison of our measurements (Figure 5) with those of *Fouch et al.* [2000] shows a measure of disagreement. We were able to resolve splitting parameters for a number of phases that are reported as "nulls" by *Fouch et al.* [2000], most likely because we used a passband that is richer in high frequencies. Frequency dependence in splitting parameters was shown by *Marson-Pidgeon and Savage* [1997] to influence parameter retrieval. In particular, *Levin et al.*, [1999] showed that splitting parameters estimated from synthetic seismograms simulated in the HRV anisotropic model become progressively less stable as the higher frequencies of the input pulse are removed. The results of this study, as well as our previous examination of data from the two long running stations HRV and PAL [*Levin et al.,* 1999], indicate that azimuthal variation in shear wave splitting occurs, and must be factored into data interpretation. We find that the vertical stratification of anisotropic parameters is required at all sites and that the character of this stratification varies only slightly over the investigated region. Our results for the northeastern United States indicate that neither surface geology nor the distribution of the shear velocity at depth seems to govern the distribution of anisotropy.

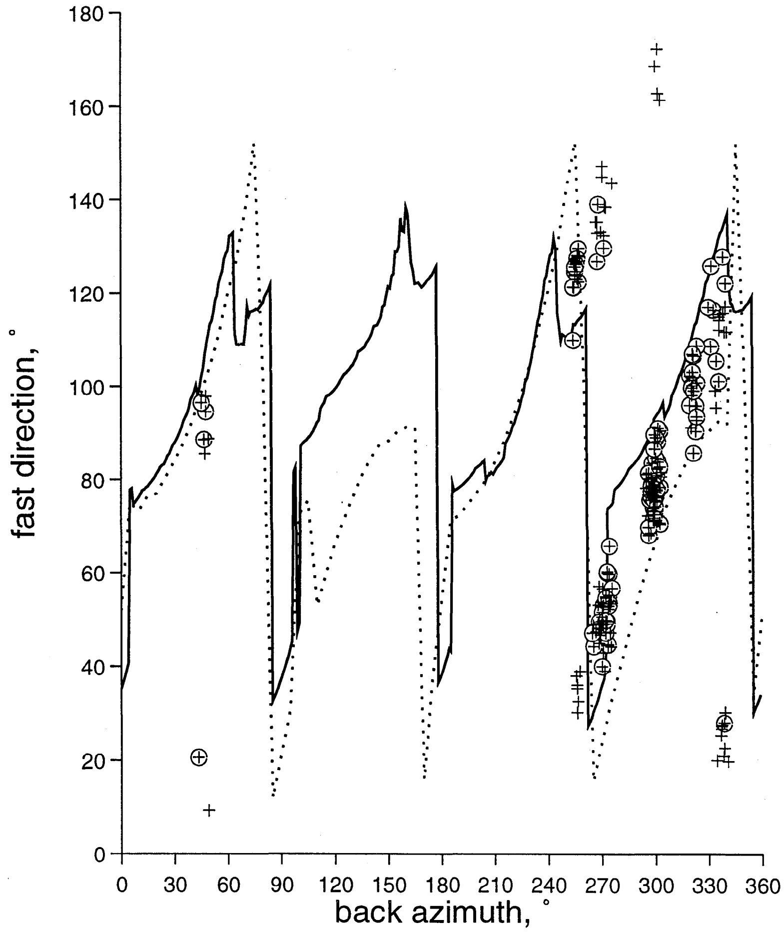

Figure 8. Variation of fast direction with back azimuth. All stations in the region appear to have the same pattern. Pluses show all measurements, and circles identify measurements with $\sigma_\tau < \tau/3$. Predicted patterns of fast direction variation for two-layer models with hexagonal (dotted line) and orthorhombic (solid line) symmetries match the observations. The model was developed for station HRV [*Levin et al.*, 1999], and is presented in Table 3.

Although its poor correlation with apparent isotropic velocity variations is unambiguous, our anisotropy model has other ambiguities. Splitting times constrain the product of layer thickness and shear anisotropy, so there is a trade-off between them. The order of anisotropic layers is constrained by the splitting pattern, but their precise depth ranges are not. A model with two anisotro-pic layers provides a significantly better fit to 7 years of shear wave splitting observations at GSN station HRV than do models with a single anisotropic layer [*Levin et al.*, 1999], but more complex structures are not ruled out. Within the limited context of two-layer anisotropy models, the HRV splitting data constrain the fast axis orientation within each layer to ~10° uncertainty. However, our data set is sparse, so additional anisotropic heterogeneity (e.g., finer layering, unsampled geographic regions with unusual strain) may be present. Finally, *Levin et al.* [1999] found that models with orthorhombic and hexagonal symmetry could not be distinguished with splitting data from HRV. The fast axis strikes for the two symmetry types agreed well, however.

As discussed in the introduction, near-uniform anisotropic parameters over a broad region suggest a dynamic origin of the underlying mantle fabric [*Vinnik et al.*, 1992]. It appears natural to associate the fast direction orientation in the lower layer of the model (N53°E) with passive mantle shear under the North American continent, aligned with the absolute plate motion vector of ~N245° E [*Gripp and Gordon*, 1990]. Interpreting the upper layer of the model in terms of dynamic fabric is problematic, though, as it would require two regions with distinctively different strain to exist one above the other in the mantle. Placing the upper layer of our model within the consolidated lithosphere of the continent raises another problem: The sense of fabric in this layer needs to be relatively uniform throughout the region composed of various tectonic units and characterized by significant seismic velocity variations. Given the diversity of ages and tectonic histories of the con-

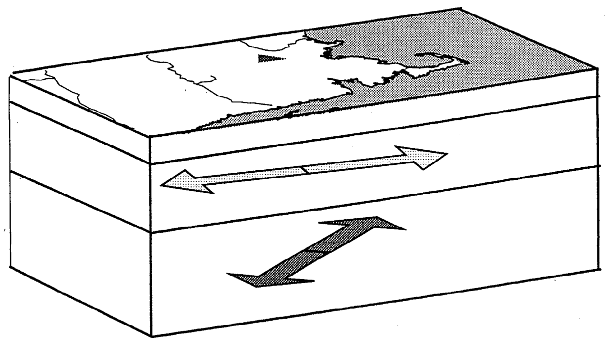

Figure 9. A schematic representation of the model for seismic anisotropy distribution under HRV. Station location is indicated by the triangle. See Table 3 for model parameters.

stituent tectonic units, it is reasonable to assume that the fabric-forming event should postdate the assembly of the region in present form.

Two possible causes for the anisotropy are (1) a continent-continent collision during the final stages of the Appalachian Orogeny and (2) the rifting that led to the eventual opening of the Atlantic Ocean. Continental collisions are believed to result in orogen-parallel flow in the mantle [*Vauchez and Nicolas*, 1991]. For option 1 to fit all data, the inherited mechanical anisotropy of the Grenville lithosphere [e.g., *Barruol et al.*, 1997b] would need to resemble that acquired during the Appalachian Orogeny. However, the fast axis orientation of the upper layer (N115°E) is nearly normal to the strike of the tectonic units in the region, and normal to a hypothetical orogen-parallel fabric. Similarly, studies of shear wave splitting in the regions of active rifting [*Sandvol et al.*, 1992, *Ben Ismail and Barruol*, 1997] report fast axis directions aligned along the axis of the rift. This would be approximately north-south in our region, a poor match to the observed fast axis direction in the "frozen-fabric" upper layer.

Levin et al. [2000] proposed postcollisional deformation of the Appalachian Orogen as an alternative mechanism for generating orogen-normal mantle fabric

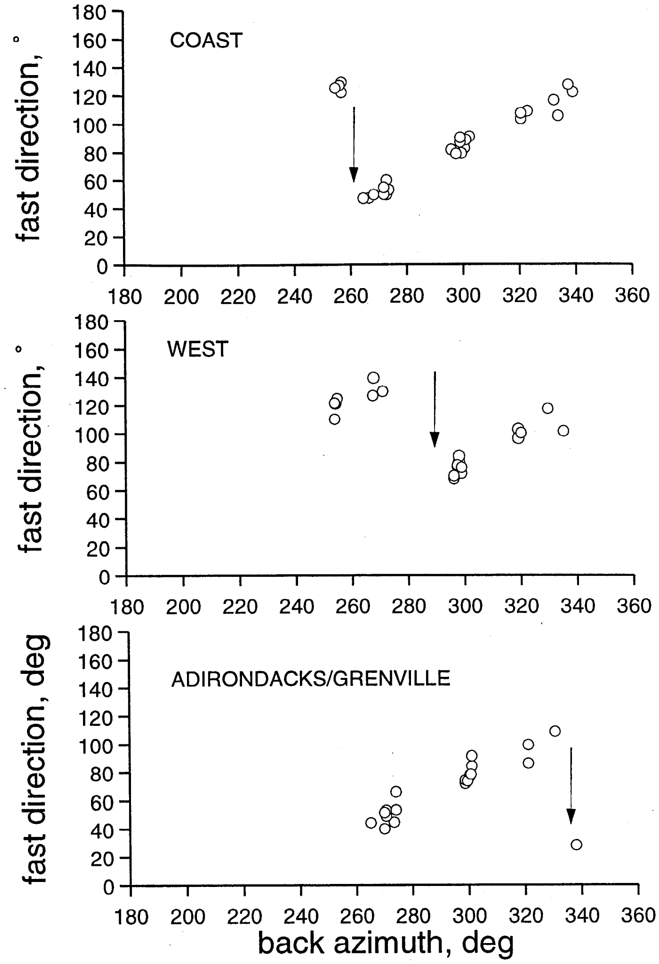

Figure 10. Regional variation in the pattern of fast direction change with back azimuth. Only high quality observations (circles from Figure 8) are retained.

in the "frozen" lithosphere. Geodynamic models for present-day uplift in the Tibetan Plateau, the western United States and elsewhere have posited mechanisms for removing the mantle lithosphere beneath a continent-continent collision zone, and replacing it with warmer asthenospheric rock [e.g. *Molnar et al.*,

Table 3. Anisotropic Structure (Orthorhombic Symmetry) Consistent With Shear Wave Splitting Observations at HRV

Depth, km	V_p, km/s	V_s, km/s	ρ, g/cm^3	θ_f, deg	ϕ_f, deg	θ_i, deg	ϕ_i, deg	θ_s, deg	ϕ_s, deg
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	...	...	...	...	...	...

Velocity values in anisotropic layers are the isotropic averages of respective elastic tensors. Depth to the bottom of each layer is shown. The anisotropic medium is modeled as 30% orthorhombic olivine and 70% isotropic olivine, a mixture that is ~6% anisotropic. The angles θ and ϕ define the tilt (from vertical) and azimuth (clockwise from north) of the symmetry axes (fast, intermediate, slow) within each anisotropic layer.

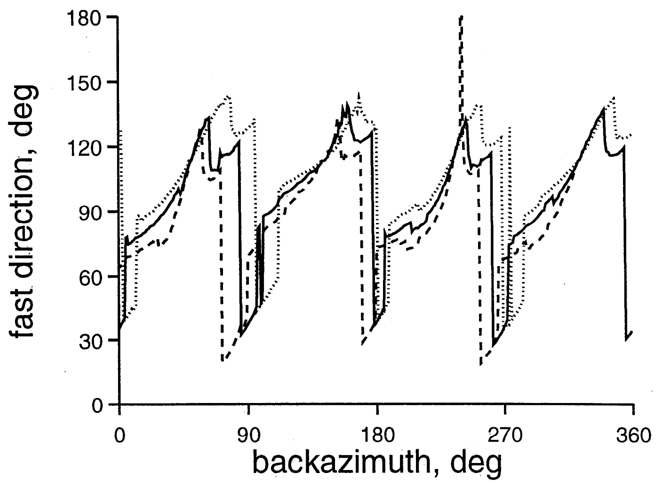

Figure 11. Changes in the pattern of fast direction change with back azimuth resulting from minor perturbations to the anisotropic model shown in Figure 9 and in Table 3. Thicknesses of two anisotropic layers in the HRV model (solid line) were perturbed by ± 10 km, with the total thickness of the model being preserved. Dashed line shows a case of the thinner upper layer; dotted line - a thicker upper layer. The deviations of the pattern are comparable to those seen in the data.

1993]. Patterns of magma emplacement, particularly mantle-derived melts, that hypothetically would follow this replacement have been recognized in recent Tibetan volcanism [*McKenna and Walker*, 1990; *Arnaud et al.*, 1992], and also in the late Paleozoic mountain belts that mark the final closure of the Iapetus Ocean at ~ 400 Ma [*Wenzel et al.*, 1997; *Ajaji et al.*, 1998; *Chalot-Prat*, 1995; *Pe-Piper and Piper*, 1998].

Most popular mechanisms for shedding mantle lithosphere imply substantial shear of the remaining subcrustal mantle. *Houseman et al.* [1981] proposed that a thickened root of the mantle lithosphere forms during continent-continent collision. This cooler rock mass would be convectively unstable, and could drop off as a downgoing plume on 10–50-My timescales [*Conrad and Molnar*, 1997]. Computer simulations of this process suggest significant shear in the continental lithosphere left behind, as well as within the asthenospheric replacement material. Alternatively, the mantle root may delaminate from the overlying crust and uppermost mantle [*Bird*, 1979], perhaps detaching within the ductile lower crust [*Meissner and Mooney*, 1998]. Recent computer simulations of this process [*Schott and Schmeling*, 1998] show that a region of significant strain directed toward the center of the orogen forms along the plane of future delamination and detachment, involving the entire width of the orogen. The slab-rollback model [*Willett and Beaumont*, 1994] does not require formation of a mantle root, but rather the shedding of the downgoing slab attached to the underthrusting plate. Slab descent would draw in asthenospheric mantle beneath the margin of the overriding plate, leading to uplift and orogen-normal extension.

Considering the broad deformation of the Tibetan uplift as an example, if the loss of continental mantle indeed occurred under the New England Appalachian

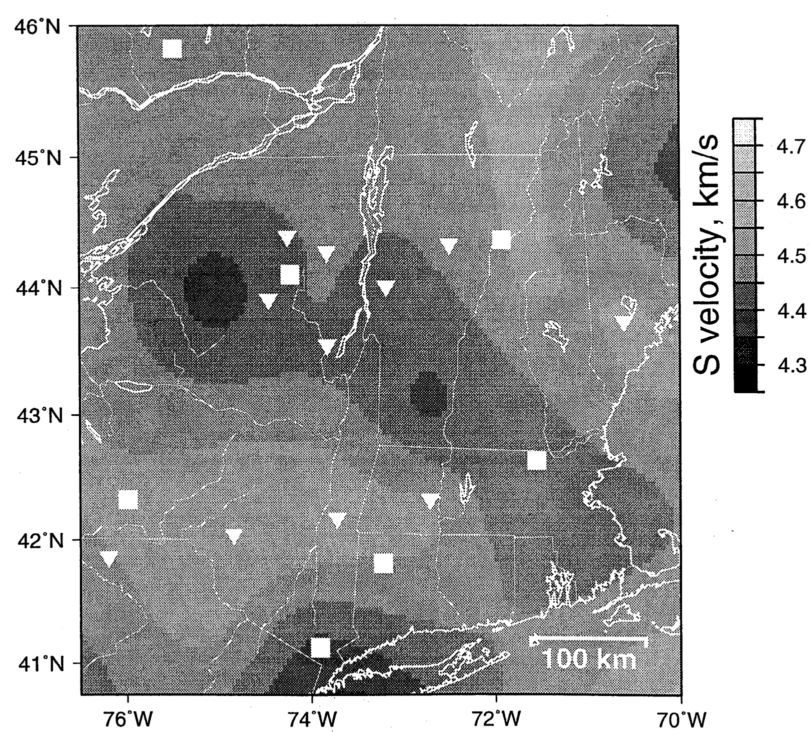

Figure 12. Distribution of shear velocity in the best resolved region of the tomographic model (100 - 200 km deep). Velocity varies by $\pm 3\%$, with lateral scale of anomalies being between 100 and 200 km.

Orogen, it would likely have involved the Grenvillian terranes on its flanks as well as the younger terranes in the center. The Tibetan parallel fails, however, to explain the orogen-normal fast axis that we place in the northeastern U.S. lithosphere. In Tibet the fast axes are orogen-parallel, which may reflect eastward extrusion of the plateau and its underlying lithosphere [*Lave et al.*, 1996; *Meissner and Mooney*, 1998; *Holt*, 2000]. Such 3-D "escape tectonics" has also been recognized in the late Paleozoic orogenies [*Brechner et al.*, 1998; *Keppie*, 1993] coeval with the Appalachian orogeny. However, there is no reason to assume that significant 3-D mantle flow will develop in every case. The simple conceptual models for mantle delamination and/or rollback are two-dimensional, and predict orogen-normal mantle strain, not orogen-parallel strain. A uniform east-west extensional strain fabric would remain in the "scarred" Appalachian lithosphere, assuming that the flow retained a rough 2-D geometry beneath the orogen.

5. Summary

On the basis of data collected by a composite network of broadband seismic stations, we investigated the relationship between the shear velocity distribution and the parameters of shear wave splitting in a stable continental region, testing the viability of the "anisotropic domains" hypothesis. We found that the region we examined, the northeastern United States, is characterized by a surprisingly uniform anisotropic signature. While shear wave splitting parameters vary with back azimuth at every station in our network, the pattern of this variation is very similar throughout the region. A simple one-dimensional model containing two layers with different anisotropic properties fits this pattern very well. We found that the isotropic shear velocity varies on a length scale of 100–200 km in this region, in contrast to the muted lateral variability in anisotropy. There appears to be little or no correlation between the "rough" structure in isotropic seismic velocity and the smoothly varying anisotropic signature consistent with shear wave splitting. The paradigm of "anisotropic domains" implies a regionalization of strain within the upper mantle caused by present-day complexity in mantle flow or by distinct terrane deformation histories. Although the sparseness of our data set could leave some significant strain heterogeneity undetected, we are led to conclude that the concept of "anisotropic domains" does not apply in the northeastern United States. The upper layer of mantle strain in our model is likely fossil, and its apparent spatial uniformity implies an anisotropy that developed after terrane assembly and the closing of the Iapetus Ocean. Postcollisional loss of the continental mantle root in the late Paleozoic via convective instability, delamination, and/or slab rollback are plausible mechanisms for the inferred "frozen" lithospheric strain.

Acknowledgments. We thank Mr. and Mrs. Barstow of Adamant, Vermont and Mr. and Mrs. Estes of Standish, Maine for hosting temporary-deployment seismic stations in 1995. K. Fischer and S. Roecker kindly provided data from their portable networks prior to the public release. R. Hartog, R. Russo, and the associate editor Susan Schwartz provided helpful reviews. We thank M. Brandon for insightful discussions regarding delamination scenarios. We used GMT software [*Wessel and Smith*, 1991] to prepare figures. This work has been supported by NSF grant EAR-9707189. Array operation by V.L. and W.M. in 1995 was supported in part by the grant from Sigma Xi Grants-in-Aid program.

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(Received May 28, 1999; revised March 7, 2000; accepted April 5, 2000.)