Seismic Evidence for Upper Mantle Extension Beneath the Late Paleozoic Appalachian Orogen.

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Abstract

Across the Appalachian orogen of New England, the splitting of core-refracted shear waves from a wide range of arrival directions indicates the presence of two near-uniform horizontal layers of anisotropic upper mantle. The anisotropy in the lower layer has a fast axis near-parallel to the motion of the North American plate in an absolute reference frame, and thus is attributed to basal shear as the plate plows through asthenospheric mantle. The anisotropy of the upper layer is inferred to be a fossil fabric, residing in lithospheric mantle. The finite extension direction of the upper fabric is subhorizontal and oriented normal to the local trend of the Appalachian orogen. The upper fabric is consistent over a broad region beneath and west of the New England Appalachians, which indicates that it formed after Devonian closure of the Iapetus Ocean, probably during the late Paleozoic Acadian and Allegenian orogenies. Tectonic scenarios for syn-convergent extension predict rapid surface uplift and increased heat flow due to lithospheric thinning, which may account for late-orogenic mantle-derived magmatism that occurs in both the northern Appalachians and Morocco.

Introduction

Finite strain in the Earth's upper mantle causes lattice-preferred orientation (LPO) of olivine, which is the dominant mineral in the upper mantle (Zhang and Karato, 1995). As a result, highly-strained mantle rocks are expected to have a bulk elastic anisotropy with approximate axial symmetry, with maximum seismic velocity parallel to the maximum extension direction (Ribe, 1992). Anisotropic media "split" a propagating shear wave into two orthogonal time-shifted pulses, with particle motion aligned with "fast" and "slow" polarizations in the medium (Vinnik et al, 1984). Path-integrated seismic anisotropy can be estimated most readily from shear waves that enter an anisotropic region with a known polarization e.g., core-refracted SKS. Splitting observations in orogenic zones have often, but not universally, indicated a fast axis parallel to the orogen, consistent with collisional shortening of the mantle "root" (Silver, 1996).

Initial shear-wave splitting observations from the northeastern United States have led to a range of interpretations for the underlying mantle fabric. These include strain associated with present-day absolute plate motion (Fischer et al, 1996) and fossil strain acquired during the Appalachian orogenies (Barruol et al, 1997). Splitting measurements from shear-waves from numerous backazimuths are better fit with two layers of anisotropic rock (Levin et al 1999a; Fouch et al., 1999). We combined data from two long-running permanent seismic observatories with observations from a two-dimensional temporary seismic network that collected data in spring/summer 1995, and derived a vertically layered anisotropic model for the northeastern US in which both modern and fossil deformation appear to play a role. The inferred mantle strains are near-uniform across a broad region of the northeast United States, in contrast to significant variations in basement geology (from the Precambrian Grenville Province in the west to the Avalonian terrane in the east) and in the travel-time delays of seismic body waves (Levin et al, 1995a, 1999b). The near-uniformity in anisotropy suggests strongly that any fossil strain must post-date the assembly of the Appalachian orogen.

Seismic Evidence For Coherent Paleozoic Strain in the New England Lithosphere

On a single seismic record, the fast and slow polarizations of core-refracted shear waves combine to form elliptical particle motion in the horizontal plane. This waveform can be decomposed into two pulses of identical shape, shifted by time delay τ, with a coordinate rotation to an apparent fast-polarization direction ϕ. If, at a particular seismic station, ϕ and

τ for incoming shear waves are observed to be invariant over a range of back-azimuths and incidence angles, a single layer of anisotropy with a horizontal symmetry axis can be inferred beneath the station. A tilted fast axis or vertical layering of anisotropy would give rise to systematic (and distinct) variations in apparent ϕ and τ, dependent on the direction of the incoming wave (Babuska et al, 1993; Silver and Savage, 1994). This is what we observe for shear-wave splitting across the northeastern United States (Figures 2 and 3). The pattern of variation in apparent fast-axis strike ϕ is similar at all sites where broadband seismic observations are available. Estimates of splitting delay times τ from individual seismograms are less robust than estimates of ϕ, because the former depend on the choice of frequency bandpass and pulse duration (Levin et al, 1999a).

The observed pattern in fast-polarization direction ϕ at each station can be satisfied well with a model containing distinct layers with different fast-axis orientations. We developed a two-layer upper-mantle anisotropy model using the longest-running site in the region (Table 1), station HRV of the Global Seismographic Network (GSN), which has good azimuthal data coverage (Figure 2). Splitting observations constrain only the product of velocity anisotropy and layer thickness. We have fixed this tradeoff by assuming the mantle has the elastic properties of peridotite with 30% aligned orthorhombic olivine, a mixture that has $\sim 6\%$ anisotropy for shear waves. This leads to 60- and 90-km thicknesses for the upper and lower anisotropic layers of the HRV model, respectively (Table 1). Aside from distinguishing "upper" from "lower" anisotropic layers, splitting observations offer no direct constraint on layer placement within the mantle/crust seismic profile. Examination of P-to-S converted waves from the crust-mantle Moho discontinuity at HRV precludes the top layer of anisotropy from residing in the crust (Levin et al, 1999a). Some of the visual mismatch between the observed and the predicted patterns in Figure 3 stems from the variety of phase velocities for the incoming S-waves in the data; the data-fitting process compensates for this. Also, in the case of 1995 array data, a regional variation in the backazimuth pattern leads to an overlap of two data "branches" near 290^o. This can be modelled successfully with small ($\sim$10 km) variations in the layer thicknesses of the HRV model, a thinner upper (lithospheric) layer under the Adirondacks/Grenville, and thicker upper layer under other inland stations. Small regional trends in layer-anisotropies (∼1%), could also cause these variations in splitting pattern.

Our anisotropy model bears an interesting relationship to the structure and dynamics of the lithosphere in this region. The inferred fast-axis directions are horizontal in both layers. In the lower layer the fast axis azimuth (N53^{o}E) is sub-parallel to the absolute plate motion of North America (∼N65^{o}E) as reported by Gripp and Gordon (1990). In the upper layer the fast axis is near-perpendicular to the local trend of the Appalachian orogen. Levin et al (1999a) also describes a vertically statified anisotropic model with axial symmetry, simpler than orthorhombic. The fast-axis trends in the axially symmetric model are N50^{o}E and N100^{o}E for the lower and upper layers, respectively, similar to the fast-axis directions of the two-layer orthorhombic model. The axially-symmetric model fits the splitting data as well as the orthorhombic model, but requires a fast-axis in the lower layer that dips 40^o below the horizontal.

We interpret the lower layer to lie within an actively deforming asthenosphere, with anisotropic rock fabric maintained by contemporary plate motion. We interpret the upper layer to reside in the stable part of the continental lithosphere, with a frozen fabric that formed during a past deformation event. We reject two alternative tectonic interpretations. First, it is unlikely that both anisotropic layers reflect contemporary dynamics at the base of the North American plate, leading to a corkscrew shear in the underlying asthenosphere. Second, it also seems unlikely that one or both of the layers reside in the deep mantle e.g., the D" region. In order to influence SKS waves from all observed back-azimuths, the coherent lateral extent of a deep-mantle layer would correspond to a disk of diameter ∼1800 km, spanning an arc ∼30^o at the core-mantle boundary. In upper-mantle layers, by contrast, our interpretation implies lateral coherence across only the ∼5^o aperture of the stations.

Near-uniform anisotropic properties in the upper mantle beneath the northeastern US appear to contrast with significant local variations in isotropic seismic velocities in compression (Levin et al, 1995a) and shear (Levin et al, 1999b). Lateral variation in shear-wave travel-time delays suggest significant (∼3%), short-scale (∼100 km) shear-velocity anomalies in either the lower crust or upper mantle. These anomalies correlate roughly with regional geology e.g., a slow anomaly beneath the Adirondack mountains. The contrast between "rough" velocity variations, indicative of rock composition, and smooth, weak anisotropy variations, indicative of mantle strain, argues that the anisotropy developed after the Paleozoic accretion of Appalachian terranes to the Proterozoic Grenville province. The accretion of the Avalonian terrane, whose basement rocks underlie our easternmost stations HRV and STME, is estimated variously to coincide with the Acadian orogeny in New England (∼410 Ma - see Lyons et al (1982)), or with an earlier orogeny recognised in Newfoundland (late Silurian, starting 430 Ma - see Keppie (1993)), so the maximum age for the fossil strain is somewhat soft.

Mantle fast-axis directions along mid-ocean ridges are both predicted and observed to align perpendicular to the rift axis (Ribe, 1992; Wolfe and Solomon, 1998), and our upper-layer fast axis is perpendicular to the general north-south trend of the failed Connecticut Valley rift. Nevertheless, we favor the hypothesis that the upper layer of anisotropy beneath the northeast US is associated with convergent, late-orogenic tectonism in the late Paleozoic, and not with divergent, syn-rift tectonism in the early Mesozoic. Shear wave splitting studies within active continental rift zones typically indicate fast polarization aligned with the axis of the rift, not normal to it (Sandovol et al, 1992; Gao et al, 1997; Vauchez et al, 1999; Gao et al, 1999), and has been interpreted as arising from aligned melt-filled cracks. This argues that the disruption of continental lithosphere during rifting differs from the steady-state growth of oceanic lithosphere, typically involving a narrow upwelling rather than a broad mantle flow.

Post-Orogenic Mantle Extension Scenarios

There is a controversy about what happens to the excess mantle lithosphere in continent/continent collision zones. Does the continental mantle lithosphere subduct like oceanic lithosphere or does it deform with the rest of the orogen, forming a combined mantle and crust root? If the mantle lithosphere is subducted, slab "rollback" can cause widespread horizontal extension, in both the asthenosphere and mantle lithosphere (Willett and Beaumont, 1994). If mantle lithosphere does not subduct, modelling studies suggest that, after 10–50 m.y., it may founder, detach, and sink through the asthenosphere (Molnar et al, 1993; Houseman et al, 1981; Conrad and Molnar, 1997; Houseman and Molnar, 1997). Detachment might occur via ductile necking, or by delamination (Bird, 1979; Schott and Schmeling, 1998). All of these scenarios predict late- or post-orogenic lithospheric thinning, which would result in pronounced topographic uplift and near-surface extension, followed by an increase in heat flow. Such hypotheses have been invoked to explain present-day uplift of Tibet and the US Basin and Range province, as well as past uplift in the Aegean region, and the Pannonian basin.

Petrologists have attributed patterns in "late-orogenic" magmatism to the thinning of cold lithospheric mantle, and the bouyant rise of asthenosphere. The fingerprints of such magmatism point to the involvement of hot mantle in situations where one might expect collisional thickening of the lithosphere to thermally insulate the crust. These include trace-element enrichment patterns that indicate partial melting of reheated continental lithosphere, and paired mafic and felsic melts that indicate ponded asthenosphere-derived gabbroic intrusions at the base of the crust (Huppert and Sparks, 1988; McKenna and Walker, 1990; Arnaud et al, 1992; Turner et al, 1992; 1996; Liegeois et al, 1998; Sylvester, 1998; Bonin et al, 1998). A time-succession of these two types of magmatism would suggest an initial partial removal of a mantle orogenic root, followed by further convective thinning and/or ablation of the remaining continental lithosphere.

Although these different tectonic scenarios vary in detail, all are consistent with the development of similar anisotropy in the upper mantle, formed by horizontal extension of the residual mantle lithosphere or the asthenospheric flow that replaces the mantle root (Figure 4). The orogen-perpendicular fabric that developed during the extension of the Appalachian mantle differs from orogen-parallel fast axes observed in Tibet (McNamara et al, 1994; Hirn et al, 1998) and the Alps/Carpathians (Brechner et al, 1998; Dricker et al, 1999), but both those regions are thought to be influenced by orogen-parallel motion of "escaping" blocks (Meissner and Mooney, 1998). The extended length of the late Paleozoic Appalachian/Hercynian collision zone between Laurentia and Gondwana may have limited such lateral movements, and favored asthenospheric flow perpendicular to the orogen, at least locally.

Although there is no way to date the inferred mantle fabric directly, several lines of evidence suggest that stretching and uplift of the Appalachian mantle accompanied the Acadian and Alleghenian orogenies, which span the time between the final closure of Iapetus (Devonian, 390–410 Ma, depending on the reconstruction) to the cessation of thrusting, magmatism and thermal metamorphic activity in southern New England (Permian, 275 Ma). This evidence includes removal of 15 km or more of upper crust in Southern New England by erosion (Carmichael, 1978), which implies high topography during the late Paleozoic; granitic magmatism and thermal metamorphism in New England, indicating high heat flow (Zartman, 1988; Zartman et al, 1988; Lux and Guidotti, 1985; Sevigny and Hanson, 1993; Moechner et al, 1997); and late Paleozoic crustal extension in Connecticut (Getty and Gromet, 1992ab). Mantle-derived magmatism and mafic underplating have been observed or inferred, respectively, for various late Paleozoic New England igneous rocks (Hannula et al, 1998; Wiebe et al, 1997). Some large Acadian plutons show little evidence of mantle influence (Lathrop et al, 1996), but note that two of the largest, the Bethlehem Gneiss and the Kinsman Quartz Monzonite, are dated at ~410 Ma, and thus cannot be characterized as late-orogenic.

Seismic studies (Hughes and Luetgert, 1991; Hennet et al, 1991; Shalev et al, 1991; Zhu and Ebel, 1994; Levin et al, 1995b) show the lower crust of northern New England to be reflective and to lack large-scale structures e.g., throughgoing fault zones. The compressional velocity of the lower crust (~6.8 km/sec) is consistent with mafic underplating after collision and the removal of an upper mantle root. Beneath New England, Van der Lee and Nolet (1997) imaged a broad shallow (~100 km) low-velocity anomaly in shear with mantle surface waves. The size of this anomaly relative to the adjoining craton (~10%) led them hypothesize that volatiles, released by a long-departed slab during the Paleozoic closure of the Iapetus Ocean, have lowered the peridotite seismic velocity. However, high-pressure mineral elasticity experiments suggest that the major-element compositional differences that distinguish "undepleted" from "depleted" mantle peridotite could also explain a large portion of this anomaly (Chai et al. 1997; J. Michael Brown, personal communication). In our late-orogenic mantle extension scenario, the low velocities observed by Van der Lee and Nolet (1997) arise largely from the post-collision replacement of depleted lithospheric mantle with undepleted "asthenospheric" rock.

To the northeast of our seismic data where crustal erosion is less deep, Devonian continental tholeiites, inferred to represent partial melt of the underlying lithosphere, are reported in the Canadian Magdalen basin, as well as later mixed mafic and felsic magmas, indicative of gabbroic underplating of the crust (Pe-Piper and Piper, 1998). Dextral transcurrent motion along faults within the Meguma terrane in Nova Scotia has been dated to occur in several episodes that span 270–370 Ma, suggesting some orogen-parallel motion of crustal blocks within an evolving collision zone (Keppie, 1993), but these structures lie northeast of our seismic stations. On the African side of the orogen, Hercynian volcanics have been identified in Morocco, and include both calc-alkaline (shoshonitic) sequences (344 Ma - see Ajaji et al (1998)) and mixed mafic/felsic magmas indicative of mafic underplating (290 Ma and 325 Ma – see Gasquet et al (1992) and Chalot-Prat (1995), respectively).

Conclusion

Continental delamination has been proposed to explain the regional geology of the New England Appalachians (Robinson, 1993), but the potential impact of upper-mantle tectonics has not been evaluated as fully as for many coeval locales in Canada (Lynch and Tremblay, 1994; Lynch and Giles, 1995; Murphy et al, 1999) and in Europe (Wenzel et al 1997). Deployments of broadband seismometers at other locations along the orogen will be necessary to map further the upper-mantle strain "scars" of the Appalachians, and to discover more clues to their history. More than 100 My of plutonism and tectonic activity follows the accretion of the Meguma terrane, which marked the final closure of the Iapetus ocean. During this interval, orogenesis continued as an intra-plate process within the supercontinent Pangaea, with a muted connection to global-scale plate movements. Our seismic anisotropy model motivates our hypothesis that hot asthenosphere replaced cooler continental lithosphere in the northern Appalachians during the late Paleozoic, and later cooled to form new lithosphere. This process, similar to spackle applied to repair damaged plaster, may have an important role in continental dynamics.

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Table 1: *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 ~6% anisotropic. The angles θ and ϕ define the tilt (from vertical) and azimuth (CW from north) of the symmetry axes (f=fast, i=intermediate, s=slow) within each anisotropic layer.

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	-	-	-	-	-	

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Figure Captions

Figure 1. Map of station network. Major tectonic boundaries for the Northern Appalachian orogen are indicated. The dashed boundary indicates the inferred extent of Avalonian basement in southern New England (Lyons et al, 1982). Horizontal projections of our best-fit anisotropic fast-axis directions are indicated with double-headed arrows within the cluster of station locations (triangles). The light arrow represents the top layer. The shaded arrow represents the bottom layer. The dashed ellipse within stable North America indicates the Adirondack Mountains.

Figure 2. Observed (solid) and predicted (shaded) shear wave splitting data for HRV. *S* phases from South American earthquakes with hypocenters deeper than 500 km are included

to provide coverage from the south. Splitting values are shown as bars centered on the nominal back azimuth and apparent velocity (from IASPEI91 velocity model). The bar orientation parallels the azimuth ϕ of the fast direction. Bar length is proportional to the time delay τ. Near-zero splitting delays are plotted with open circles.

Figure 3. Observed and predicted variation of the apparent fast direction. *Left:* data for station HRV, covering 1990-1997. Observations are shown by triangles with error bars. A subset of "robust" data points (circled) is indicated for which $\sigma_\tau < \tau/3$. Clearly, robust and "poor" data points follow the same pattern. Crosses show values of the fast-axis azimuth ϕ reported for HRV by Barruol et al. (1997). *Right:* data for all stations (see Figure 1) observed during the spring and summer of 1995. Crosses show all measurements, circles identify measurements with $\sigma_\tau < \tau/3$. All stations in the region follow the same general pattern. Solid lines on both plots show a pattern of fast direction values predicted by our model of seismic anisotropy (Table 1), for one value of phase velocity.

Figure 4. End-member models for extension of the upper mantle beneath a convergent orogen. Thin lines in the upper mantle represent the deformation of an originally horizontal set of material lines. Convergence of the lines indicates a component of extension parallel to the lines. Panel a): The rollback model argues that after initial collision, lithospheric mantle continues to subduct due to its greater density relative to surrounding asthenosphere. Rollback or retreat of the mantle slab away from the orogen (Willett and Beaumont, 1994). induces horizontal extension in the asthenosphere as it flows to fill the gap beneath the orogen. Panel b): detachment models argue that continental lithospheric mantle stops subducting following collision, and instead forms an orogenic root. This mantle root is negatively bouyant, and detaches from the lithosphere given time for thermal softening and viscous flow. Panel c) shows this detachment as a ductile necking instability (e. g. Houseman and Molnar, 1997). Others have suggested that detachment occurs in a more "brittle" fashion, by delamination near the surface e.g., within the lower crust (Schott and Schmeling, 1998). The residual mantle lithosphere and the asthenosphere that flows in behind should both develop a deformation fabric that would be characterized, at the regional scale, by a near-horizontal extension direction.

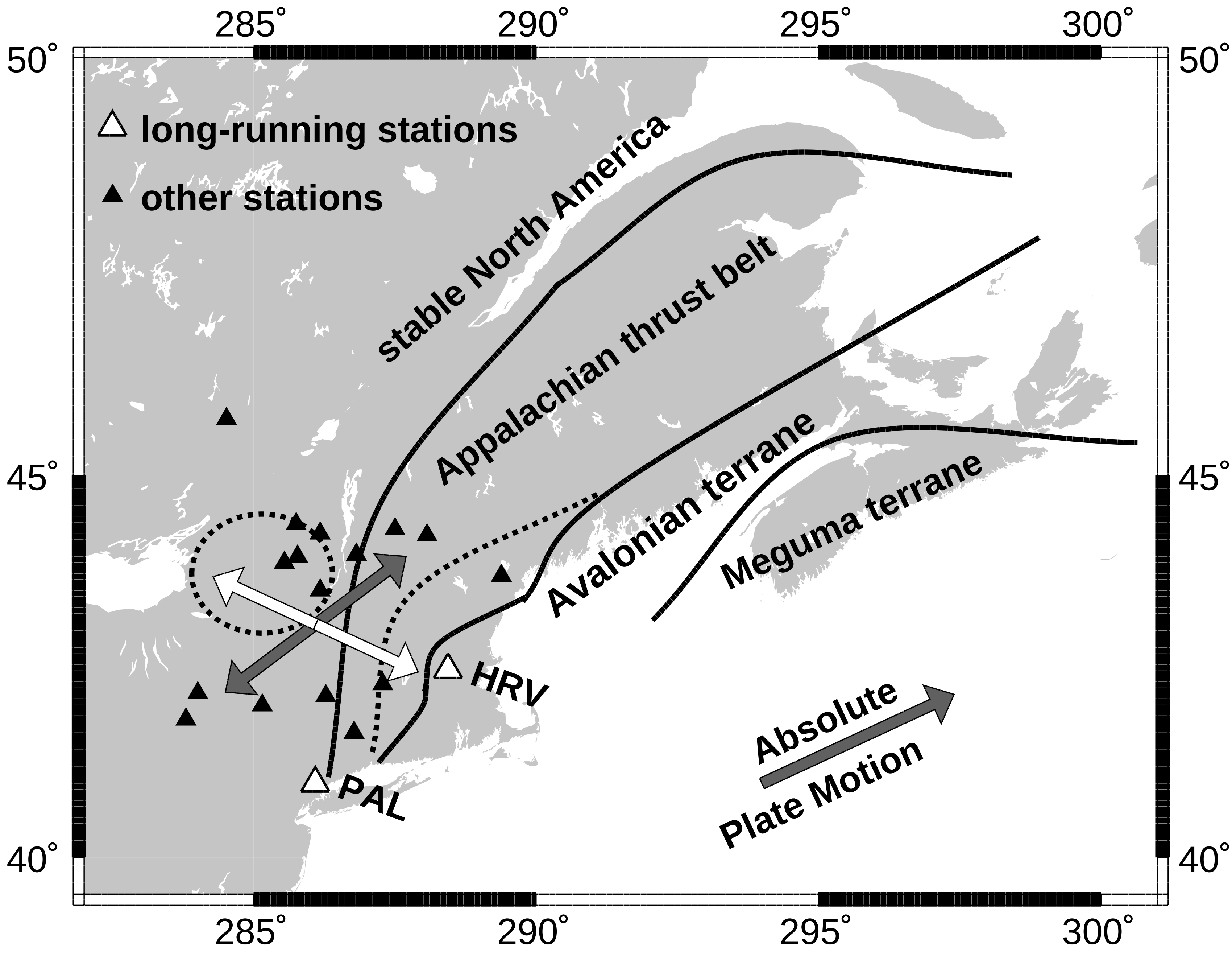


Figure 1 - Levin, Park, Brandon, Menke

Figure 2 - Levin, Park, Brandon, Menke

Shear wave splitting at HRV

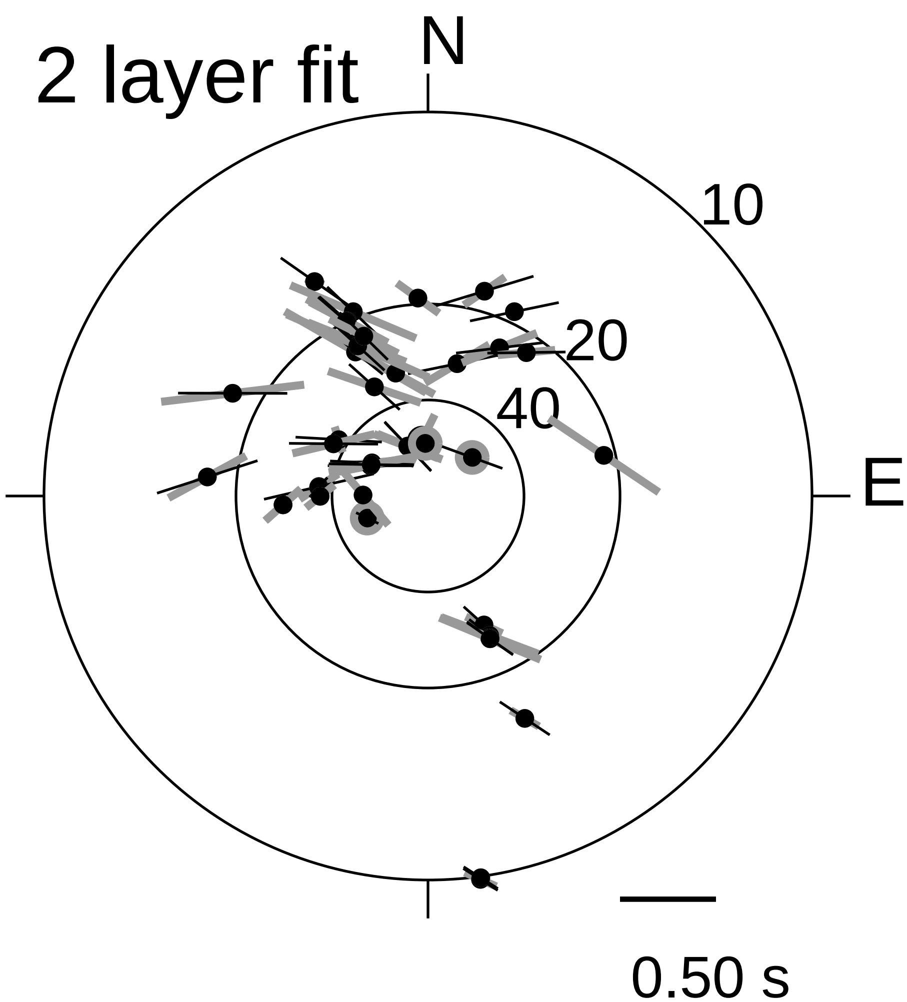
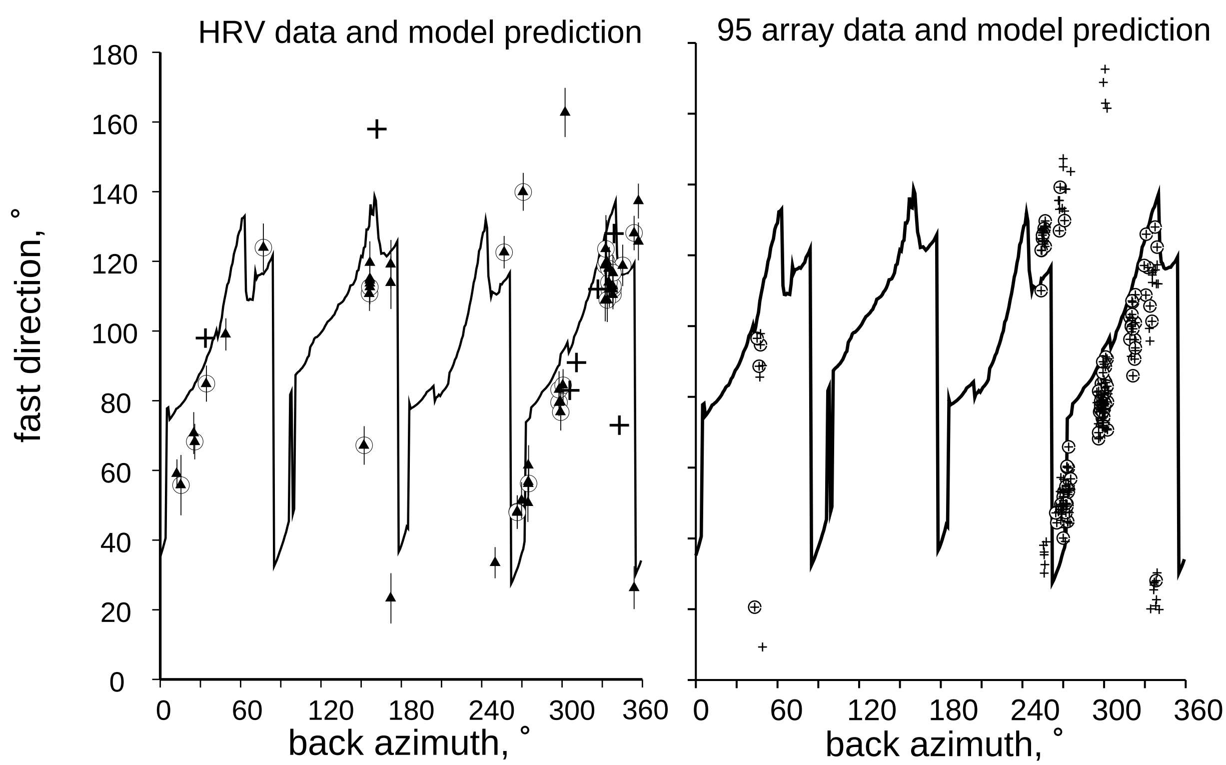


Figure 3 - Levin, Park, Brandon, Menke



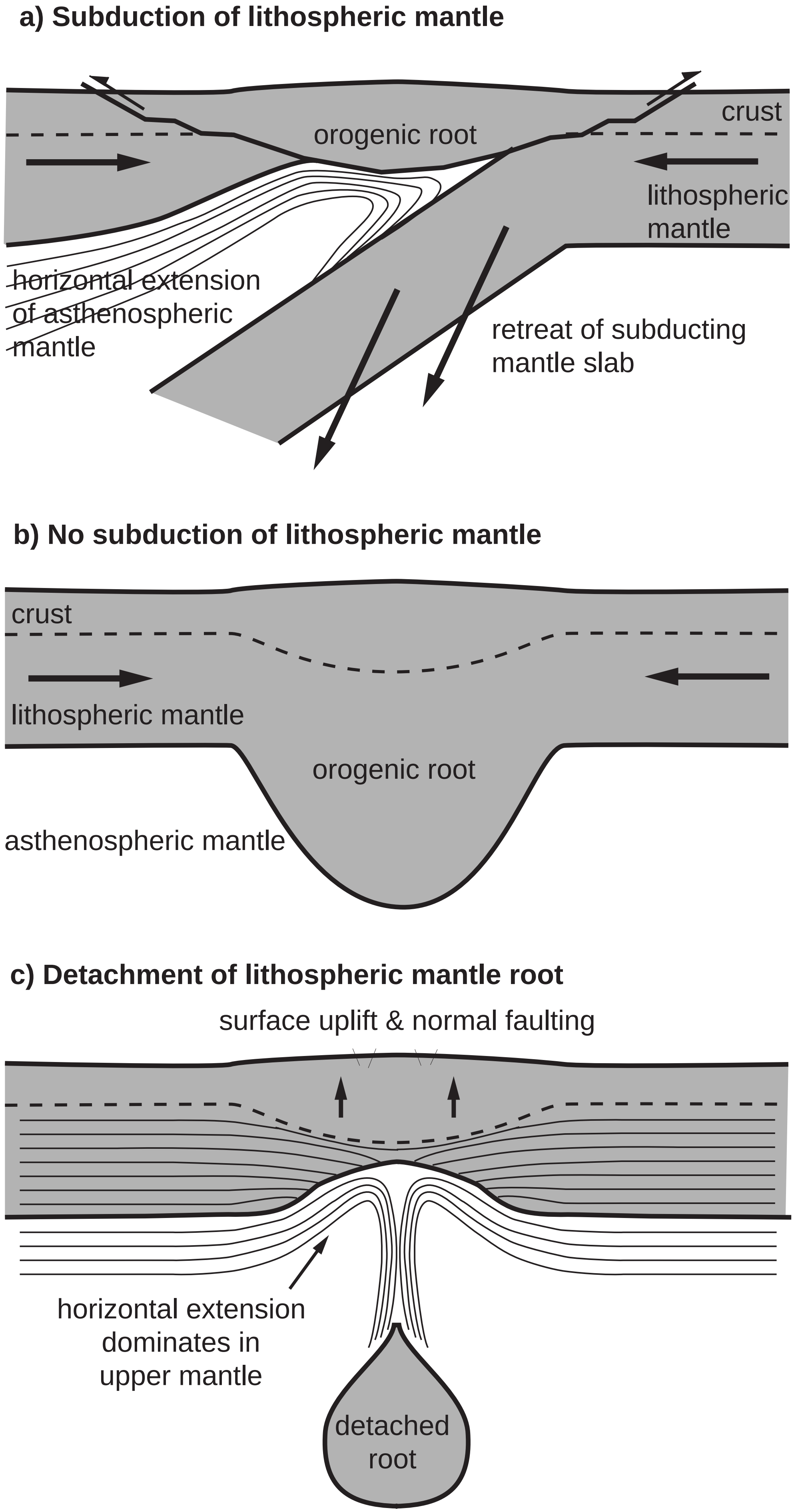


Figure 4 - Levin, Park, Brandon, Menke