Thinning of the upper mantle during late Paleozoic Appalachian orogenesis

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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 nearly uniform horizontal layers of anisotropic upper mantle. The anisotropy in the lower layer has a fast axis nearly parallel to the absolute motion of the North American plate 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 or after the Paleozoic Acadian and Alleghany orogenies. Tectonic scenarios for syn-convergent or postconvergent extension, developed for Tibet, predict rapid surface uplift and increased heat flow due to lithospheric thinning, consistent with coeval late orogenic mantle-derived magmatism in both the northern Appalachians and Morocco.

Keywords: shear waves, anisotropy, Appalachians, orogeny, Paleozoic, delamination.

INTRODUCTION

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, modeling studies suggest that, after 10–50 m.y., it may founder, detach, and sink through the asthenosphere (Molnar et al., 1993; Houseman and Molnar, 1997). Detachment might occur via ductile necking, or by delamination (Bird, 1979; Schott and Schmeling, 1998). All scenarios predict synorogenic or postorogenic lithospheric thinning, uplift, near-surface extension, and substantial mantle strain (Fig. 1).

Mantle delamination has been proposed to explain the regional geology of the New England Appalachians (Robinson, 1993), and similar ideas have been considered for the Canadian Appalachians (Lynch and Giles, 1995; Murphy et al., 1999) and in Europe (Wenzel et al., 1997). More than 100 m.y. of plutonism and tectonic activity followed the final closure of the Iapetus ocean. During this interval, Appalachian orogenesis continued as an intraplate process within the supercontinent Pangaea, with a muted connection to global-scale plate movements.

In the lithosphere beneath old orogenic belts, fossil strain should be detectable in the form of seismic anisotropy, caused by lattice-preferred orientation of olivine (Zhang and Karato, 1995), the mineral fast axes of which tend to align with the axis of maximum extension (Ribe, 1992). Anisotropy estimated for orogenic zones from the birefringence, or splitting, of seismic shear waves has often, but not universally, indicated an olivine fast axis parallel to collisional orogens, consistent with convergent shortening of the mantle root (Silver, 1996). In contrast, the mantle thinning scenarios in Figure 1 would be indicated by a fast axis perpendicular to the orogen.

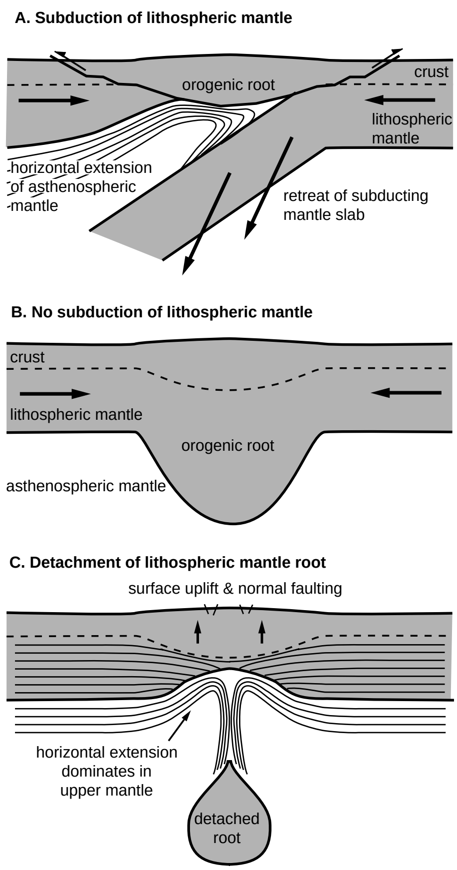


Figure 1. End-member models for thinning of upper mantle beneath convergent orogen. Thin lines in upper mantle represent deformation of originally horizontal set of material lines. Convergence of lines indicates component of extension parallel to lines. A: Rollback. After initial collision, lithospheric mantle continues to subduct due to its greater density. Rollback of mantle slab away from orogen induces horizontal extension in asthenosphere as it flows to fill gap. B: Detachment. Subduction halts following collision, and continental lithospheric mantle forms negatively buoyant orogenic root. Root detaches from lithosphere via thermal softening and viscous flow. C: Detachment is shown as ductile necking instability, but delamination near surface, e.g., within lower crust, is also possible. Both residual mantle lithosphere and inflowing asthenosphere develop deformation fabric that would be characterized, at regional scale, by nearly horizontal extension direction.

SEISMIC EVIDENCE FOR COHERENT PALEOZOIC STRAIN IN THE NEW ENGLAND LITHOSPHERE

Early observations of shear-wave splitting from the northeastern United States were attributed to either present-day strain associated with absolute plate motion (Fischer et al., 1996) or fossil strain acquired during the Appalachian orogenies (Barruol et al., 1997). When split shear waves from a larger set of earthquakes are analyzed, the apparent fast axes of individual shear waves vary with their back azimuth in a pattern diagnostic of two layers of anisotropic rock (Levin et al., 1999a; Fouch et al., 1999; see Fig. 2). To study the lateral variation of this anisotropy, we combined data from two long-running permanent seismic observatories with observations from a temporary seismic network (Fig. 3). We find that variations in apparent fast-axis strike ϕ at all stations are consistent with the two-layer anisotropic model derived by Levin et al. (1999a) for station HRV alone (Fig. 4). Estimates of splitting delay times τ from individual seismograms are more variable, but are less robust than estimates of ϕ, because the former depend more on frequency bandpass and pulse duration.

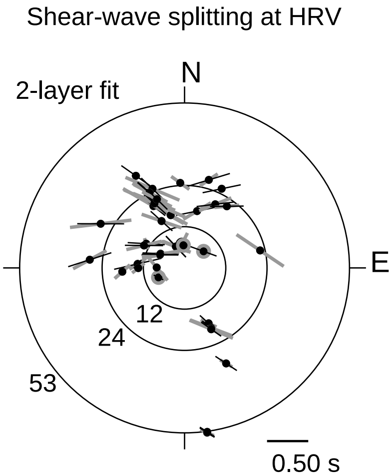
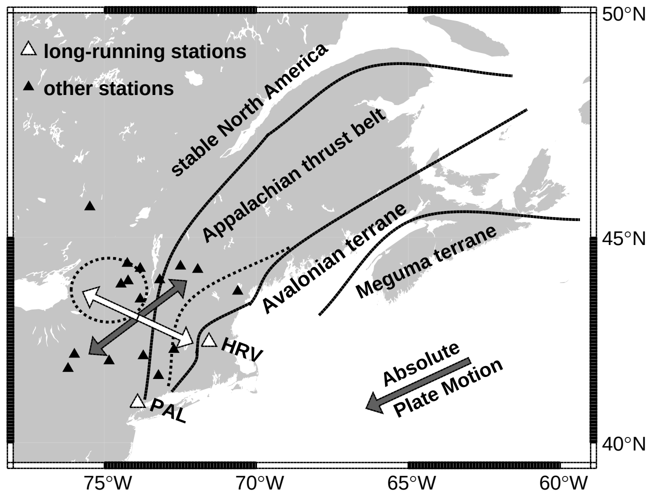


Figure 2. Observed (solid) and predicted (shaded) shear-wave splitting data for station HRV. S phases from South American earthquakes with hypocenters deeper than 500 km are included to provide coverage from south. Splitting values are shown as bars centered on nominal back azimuth (direction toward earthquake) and incidence angle (angle raypath of phase makes with vertical). Latter is computed at crust-mantle boundary on basis of IASPEI91 velocity model. Bar orientation parallels azimuth ϕ of fast direction. Bar length is proportional to time delay τ. Near-zero splitting delays are plotted with shaded circles.

Figure 3. Map of station network. Major tectonic boundaries for Northern Appalachian orogen are indicated. Dashed boundary indicates 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 cluster of station locations (HRV, PAL—triangles). Light arrow represents top layer. Shaded arrow represents bottom layer. Dashed ellipse within stable North America indicates Adirondack Mountains.



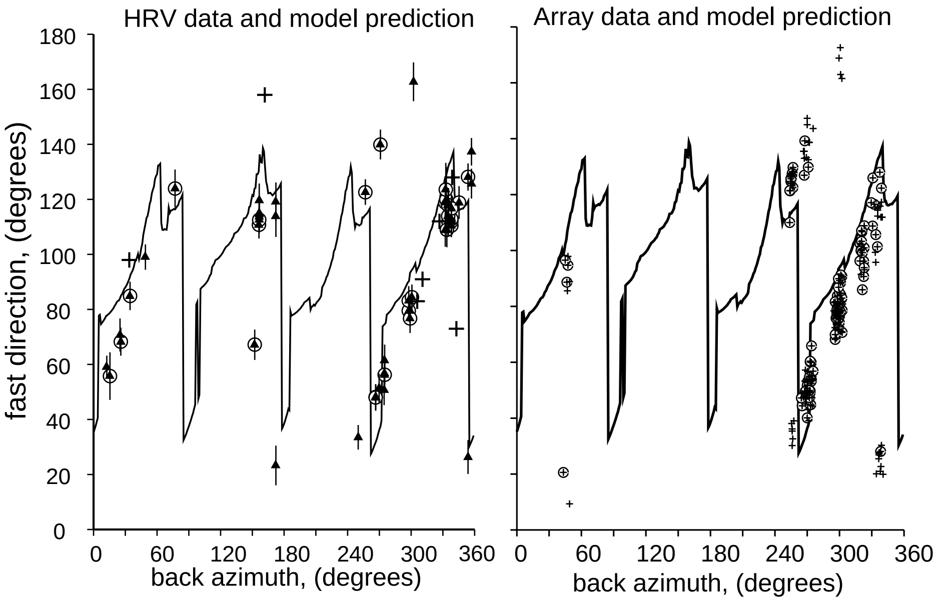


Figure 4. Observed and predicted variation of apparent fast direction. Some of visual mismatch between observed and predicted patterns stems from variety of incidence angles for incoming S waves; data-fitting algorithm compensates for this. Left: Data for station HRV, covering 1990–1997. Observations are shown by triangles with error bars. Subset of robust data points (circled) is indicated for which $\sigma_\tau < \tau/3$. Clearly, robust and poor data points follow same pattern. Crosses show values of fast-axis azimuth ϕ reported for HRV by Barruol et al. (1997). Right: Data for all stations (see Fig. 1) observed during spring and summer of 1995. Crosses show all measurements; circles identify measurements with $\sigma_\tau < \tau/3$. All stations in region follow same general pattern. Solid lines on both plots show pattern of fast direction values predicted by our model of seismic anisotropy (Levin et al., 1999a, Table 2), for one value of phase velocity.

Aside from distinguishing upper from lower anisotropic layers, splitting observations offer no direct constraint on layer thickness and placement within the crust-mantle seismic profile. Examination of P to S converted waves from the Moho discontinuity at HRV precludes the upper anisotropic layer from residing in the crust (Levin et al., 1999a). We model the anisotropic mantle as 30% orthorhombic olivine and 70% isotropic olivine, a mixture that gives ~6% anisotropy. For this choice, the upper and lower layers are 60 and 90 km thick, respectively. Weaker anisotropy would imply thicker layers. The array data has regional variation, in the form of an overlap of two data branches near back azimuth 290°. This can be modeled successfully with small (~10 km) variations in layer thicknesses: a thinner upper layer under the Adirondacks and Grenville areas, and a thicker upper layer under other inland stations. Small regional trends in layer anisotropies (~1%) could also cause these variations in splitting pattern.

Our orthorhombic anisotropy model shows an interesting correspondence to the structure and dynamics of the lithosphere in this region. The fast axes are horizontal in both layers. In the upper layer the fast axis is nearly perpendicular to the local trend of the Appalachian orogen. In the lower layer the fast axis azimuth (233°) is subparallel to the absolute plate motion of North America (~245° azimuth; see Gripp and Gordon, 1990). If axial symmetry, simpler than orthorhombic, is prescribed, the fast axis in the lower layer must dip 40° below the horizontal to fit the observations (Levin et al., 1999a).

We interpret both anisotropic layers to reside in the upper mantle. Deeper layers would imply broader regions of uniform anisotropy, e.g., a coherent anisotropic layer near the core-mantle boundary would need to span a ~30° arc. We discard the idea that both anisotropic layers reflect an ongoing corkscrew-spiral shear in the asthenosphere. Instead, we interpret the lower layer to be within an actively deforming asthenosphere, with anisotropic rock fabric maintained by plate motion. We interpret the upper layer to reside in the stable part of the continental lithosphere, with a fossil fabric.

Near-uniform anisotropic properties beneath the northeastern United States contrast with regional variations of geology within the Appalachian orogenic belt, as well as with significant short-scale variations in isotropic seismic velocity (Levin et al., 1999b). 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 the Avalon terrane to the Proterozoic Grenville province.

We propose that the upper layer of anisotropy beneath the northeastern United States is associated with convergent tectonism in the late Paleozoic, not with divergent, synrift tectonism in the early Mesozoic. Mantle fast axes 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 due-north trend of the failed Connecticut Valley rift. However, 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. For example, splitting fast axes in the Arabian shield are not normal to the Red Sea rift (Wolfe et al., 1999). Shear-wave-splitting studies within active continental rift zones typically indicate fast polarization parallel the axis of the rift, not normal to it (Sandvol et al., 1992; Gao et al., 1997).

MANTLE THINNING SCENARIOS

Petrologists often attribute late orogenic magmatism to the thinning of cold lithospheric mantle, and the bouyant rise of asthenosphere. Such magmatism indicates hot mantle in situations where one might expect cool mantle due to collisional thickening. Trace element enrichment patterns have been cited to indicate partial melting of reheated continental lithosphere, and paired mafic and felsic melts to 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). Possible causes include slab rollback or partial removal of an orogenic mantle root, coupled with convective thinning and/or ablation of the remaining continental lithosphere.

Although these different tectonic scenarios vary in detail, all would develop anisotropy in the uppermost mantle, formed by horizontal extension of the residual mantle lithosphere or by the asthenospheric flow that replaces the mantle root (Fig. 1). 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), the European Alps, and the Carpathians (Dricker et al., 1999), but those regions are thought to be influenced by orogen-parallel motion of escaping blocks (Meissner and Mooney, 1998).

Several lines of evidence suggest that stretching and uplift of the Appalachian mantle accompanied the Acadian and Alleghany 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). Crustal extension is documented by Getty and Gromet (1992). High topography is implied by upper crust erosion of 15 km or more (Carmichael, 1978). Granitic magmatism and thermal metamorphism indicate high heat flow (Zartman, 1988; Zartman et al., 1988; Lux and Guidotti, 1985; Sevigny and Hanson, 1993). Studies of mantle-derived magmatism in late Paleozoic New England igneous rocks are thus far sparse, but are consistent with a mantle-thinning scenario. In the ca. 410 Ma Bethlehem Gneiss and Kinsman Quartz Monzonite, Lathrop et al. (1996) found little evidence of mantle influence. Wiebe et al. (1997), Arth and Ayuso (1997), and Hannula et al. (1998) reported evidence for mantle-derived melts and/or mafic underplating in igneous rocks that postdate collision.

In the Canadian Appalachians, where erosion is less deep, Devonian continental tholeiites, inferred to be a partial melt of the underlying lithosphere, are reported in the Magdalen basin, as well as later mixed mafic and felsic magmas, indicative of gabbroic underplating of the crust (Pe-Piper and Piper, 1998). On the African side of the orogen, Hercynian volcanic rocks have been identified in Morocco, and include both calc-alkaline (shoshonitic) sequences (Ajaji et al., 1998) and mixed mafic and felsic magmas indicative of mafic underplating (Gasquet et al., 1992; Chalot-Prat, 1995).

Seismic studies (Hughes and Luetgert, 1991; Hennet et al., 1991; Zhu and Ebel, 1994) show the lower crust of northern New England to be reflective and to lack large-scale suture structures. The compressional velocity of the lower crust (~6.8 km/s) is consistent with mafic underplating after collision and the removal of an upper mantle root. With mantle surface waves, Van der Lee and Nolet (1997) imaged a broad shallow (~100 km) deficit in shear velocity beneath New England, which they attributed to volatiles released by a long-departed slab during the closure of Iapetus. 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, 1999, personal commun.). Therefore, the low velocities could indicate the postcollisional replacement of depleted lithospheric mantle with undepleted asthenospheric rock.

CONCLUSIONS

Observations of shear-wave birefringence (splitting) on a network of permanent and temporary seismic stations are consistent with nearly uniform upper mantle strain across a broad region of the northeastern United States. This contrasts with significant variations in basement geology and traveltime delays of seismic body waves. The near-uniformity in anisotropy suggests strongly that any fossil strain must postdate the assembly of the Appalachian orogen. Vertical layering in the anisotropy indicates that both modern and fossil deformation contribute to the signal. The upper layer of deformation, which we interpret as fossil, implies maximum extension nearly perpendicular to the Appalachian orogen. Combined with the nature and timing of late Paleozoic plutonism, this suggests that hot asthenosphere replaced cooler lithosphere in the northern Appalachians during the late Paleozoic, and then cooled to form new lithosphere. This process, similar to spackle applied to repair damaged plaster, may have an important role in continental dynamics.

ACKNOWLEDGMENTS

This work was supported by National Science Foundation grants EAR-9707189 and EAR-9805206. Jay Ague advised us regarding New England geology. J. Michael Brown allowed us to quote his results before publication. Karen Fischer and Steve Roecker provided seismic data prior to its public release. We used GMT software (Wessel and Smith, 1991) to prepare figures.

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Manuscript received August 12, 1999
Revised manuscript received November 19, 1999
Manuscript accepted December 1, 1999