Results from Prior NSF Support − Part 1

Title: Collaborative Research: Complex Upper Mantle Structure Beneath Northeastern US Investigated Through Shear Wave Tomography (collaborative project between LDEO and Yale University)

Period 08/15/97−07/31/99
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Jeffrey Park & Vadim Levin (Yale), **Award Number:** EAR−9707189, **Amount** $53193.00

The purpose of this research was to test the proposition that the mantle beneath New York and Southern New England is divided into several "anisotropic domains" that are the seismic expression of the plate tectonic process of "terrain accretion". Were such the case, we would expect different directions of the shear wave fast direction and different mean shear wave velocities in each of the several terranes (whose existence has been established geologically). Thus we assembled shear wave traveltime and splitting databases for all the broadband seismic stations that were operated − even only temporarily − in northeastern North America for a 5−year period. We analyzed the splitting data by comparing it to synthetic measurements drawn from synthetic seismograms computed for anisotropic models. We tomographically inverted the traveltime data. Much of the data analysis and modeling code was custom−written (by us) for this project.

The results are quite suprising, and show:

- The pattern of shear wave fast directions across northeastern North America is very homogeneous. No anisotropic domains occur.
- At a given station, the pattern of shear wave fast directions varies rapidly with the backazimuthal angle to the earthquake epicenter. This pattern has a strong "four−theta" component that can be explained in a most excellent manner by postulating two layers of mantle anisotropy. .
- These layers are laterally homogeneous across northeastern North America.
- The top layer has a shear wave fast direction oriented toward/away from the center of the craton. We believe it to be unrelated to the dynamics of the Precambrian craton, and instead to be related to a period of intense strain experienced by all the terranes during a lithospheric delamination, likely to have occurred during the during the Appalachian orogeny.
- The bottom layer has a shear wave fast direction oriented parallel to the edge of the craton. We believe it to be related to asthenospheric flow.
- Shear wave velocities at 100 km depth are quite heterogeneous, with the western Adirondacks being particularly slow. We postulate that this is a chemical heterogeneity that is unrelated to the strain−induced anisotropy.

We have written these papers describing the results:
Levin, V., W. Menke and J. Park, 1999. Shear wave splitting in the Appalachians and the Urals: A case for multilayered anisotropy **J. Geophys. Res.** Vol. 104, No. B8, p. 17,975−17,987.
Levin, V., J. Park, M. Brandon and W. Menke, Thinning of the upper mantle during the late Paleozoic Appalachian orogenesis, **Geology**, 28, 239−242, 2000.
Levin, V., W. Menke and J. Park, No Regional Anisotropic Domains in Northeastern US Appalachians, **J. Geophys. Res.**, *105, p 19,029−19042*, 2000.

Data and other products This project collected no new data. Some software that was written for the project is available at http://www.ldeo.columbia.edu/user/menke/software/

Results from Prior NSF Support− Part 2

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Title Active Seismic Imaging of Axial Volcano, **PI's** William Menke & Maya Tolstoy

The region of Axial Volcano, Juan de Fuca Ridge region provides an excellent opportunity to study the interplay between active "hot spot" and "mid−ocean ridge" magmatic systems. Important questions include how the two magma systems are fed; their magma and heat budgets; the degree of interconnectedness (or interaction) between them; their relationship to seismicity and geodetic strains; the role of each in plate−tectonic spreading and and crustal formation; and their effect on the geochemistry (e.g. mixing, fractionation) of erupted basalts. Information on the physical layout of the magma systems is critical to the study of each of these issues. The purpose of this research was to investigate these questions through the tomographic imaging of the region using seismic data from an active seismic airgun−to−obs experiment. The experiment was remarkably successful, both in the sense that voluminous high−quality data were obtained, and in the sense that very clear signials associated with magma were detected in that data. The key elements of the new three−dimensional compressional velocity model of the Axial and Coaxial magma systems are (West, 2001):

1. **A Very Large Axial Magma Chamber.** At a depth of 2.25 to 3.5 km beneath Axial caldera lies an 8 by 12 km magma chamber containing 10−20% melt (West 2001). At depths of 4−5 km beneath the sea floor there is evidence of additional melt, in lower concentrations (a few percent) but spread over a larger area. Residence times of a few hundred to a few thousand years are implied (West et al. 2001).
2. **A smaller Coaxial Magma Chamber, unconnected with the one at Axial.** The magma chamber is loacted at the "Source Site" of the 1993 eruption (Menke et al., 2001). It is at least 6 cubic km in volume and contains at least 0.6 cubic km of melt, enough to supply at least several eruptions of size equal to the one in 1993.
3. **Several other small low velocity zones are possibly outlier magma chambers from Axial.** Two other low−velocity zones occur in the shallow crust near Axial volcano, one about 10 km north of the caldera on the North Rift, and the other about 10 km south of the caldera but displaced to the west of the South Rift (West 2001). They appear unconnected to the main Axial magma chamber and might possibly represent small accumulations of melt left over from past lateral diking events.
4. **Strong thickening of the crust beneath Axial volcano.** The crust thickens from about 6 km far from Axial to 8 km near Axial to 11 km beneath the summit (West 2001).

Publications:

1. Menke−W, Shallow crustal magma chamber beneath the axial high of the Coaxial Segment of Juan de Fuca Ridge at the "Source Site" of the 1993 eruption, submitted to Geology, 2001.
2. West−M, The deep structure of Axial Volcano, Ph.D. Thesis, Columbia University, 2001.
3. West−M; Menke−W; M−Tolstoy; S−Webb; R Sohn, Magma reservior beneath Axial volvano, Juan de Fuca Ridge is far larger than eruption size; Nature 25, 833−837, 2001.

Data and other products This project collected new data, which is freely available on−line at http://www.ldeo.columbia.edu/user/menke/AX/. Some software, including the tomograhy code, that was written for the project is available at http://www.ldeo.columbia.edu/user/menke/software/.

Rationale for the Proposed Research

This is a proposal to assemble a new data set on the structure of the lithosphere and the underlying asthenosphere at the passive margin of eastern North America, and to use these data to gain new insights into both the process of accretion of the continent and its subsequent modification by delamination, rifting and hotspot magmatism. The target is primarily the upper mantle (as contrasted to the crust). Our motivation is that structure and fabric of the mantle are key to understanding these processes, but that relevant data currently are lacking, especially at the characteristic length scales of 250 km and less. A key part of the data set assembly effort is a temporary deployment of six broadband stations that will "bridge" existing US and Canadian stations and the soon−to−be−installed Canadian POLARIS array. The combination of these three groups of stations will "illuminate" a wide swath of the continental margin, from craton to shore, and allow us to address the fundamental issues of its evolution. This work builds upon previous work done in this area by us and by others, and substantially augments it by including both cratonic and non−cratonic regions in a uniform three−dimensional study. It also employes recent methodological advances, particularly in receiver function computations, that substantially improve resolution.

Background

The northeastern edge of North America is a "textbook−case" passive margin (Grow and Sheridan, 1988). It was formed during a Mesozoic (0.2 Ga) rifting event that created the Atlantic Ocean, which was associated with voluminous mafic magmatism (see review in Mahoney and Coffin, 1997). It has experienced very little subsequent tectonic activity, the most significant event being the passage of the hot spot that formed the New England sea mounts in the Cretaceous at 0.1 Ga (the "Monteregian" or "New England" plume) (Sleep, 1990).

The continent itself consists of a central Archean craton and a sequence of younger terranes that were accreted during the last 3 Ga. The oldest of these is the Grenville province (Moore, 1986), formed at 1.2 Ga by the closure of a now−defunct ocean basin during the Proterozoic. It separates the central craton from the younger (0.3−0.4 Ga) Appalachian and Avalon terranes that were accreted during the closure of the also−defunct Iapetus ocean during the Paleozoic (Taylor, 1989) (Figure 1).

A general thinning of the continental crust from 45−50 km at the center of the craton to ~35 km at the coast to 15−20 km on the continental shelf is evident from seismic refraction data (Hughes and Luegert, 1992; Hennet et al., 1991; Keen and Barrett, 1981). The subareal thinning mostly reflects the different provenance of the several terranes, with the younger accreted terranes generally having thinner crust. The submarine thinning reflects 40−50% extension during the Mesozoic rifting event (Steckler and Watts, 1978).

Gravity data (Grow et al. 1979) are generally consistent with seismologically determined crustal thickness, and indicate that the Atlantic oceanic crust is anomalously thick (10−12 km) just east of the margin (approximately beneath the continental slope). Fifty km east of the continental margin, the Atlantic oceanic crust has normal (7 km) thickness (Morris et al., 1993).

A corresponding − though less thoroughly studied − thinning of the mantle lithosphere occurs as well. Upper mantle shear velocity models, based on long−period waveform inversion, show a general decrease in lithospheric velocity (e.g. the velocity at 100 km depth) along a traverse from the craton’s center into the eastern Atlantic (Van der Lees and Nolet, 1997).

Estimates of the vertical dimensions of the lithosphere under the eastern part of the North American craton are approximate at best. On the basis of surface wave tomography (Van der Lee and Nolet, 1997) a lower bound of 250 km appears reasonable, although resolution of these images is not as good as one would like for this purpose. Additional constraint has been recently provided by the analysis of P−S converted phases from upper−mantle discontinuities that showed the "410" discontinuity to be essentially flat (Li et al, 1998) under the continent, with an implication that the cooling effect of the continental mantle does not reach that far. It should be noted that areas under the central (thickest) part of the craton were not sampled by the study of Li et. al. (1998).

Removal of continental lithosphere by gravitational instability (variously referred to as break−off, detachment, delamination) may have substantially thinned the lithosphere of the accreted terranes. Lithospheric delamination associated with the formation of the Appalachian Orogen has been inferred in New England Appalachians (Robinson, 1993), the Meguma terrane in Nova Scotia (Keppie and Dallmeyer, 1995), the Gander zone in Newfoundland (Schofield and Lemos, 2000). Support for lithospheric mantle removal may be found in the pattern of plutonism and metamorphism in central Maine (Solar and Brown, 1999). An earlier episode of lithospheric delamination is proposed to accompany the Ottawan Orogeny that affected present−day Adirondack Mountains at 1090−1035 Ma (McLelland et al., 2001).

Thermal subsidence models indicate that the mantle lithosphere in the vicinity of the continental shelf was significantly thinned by 40−50% (e.g. by necking) during the initial stages of the Mesozoic rifting, and replaced by hotter asthenosphere (Sawyer et al., 1983). The present day lithosphere in this region may thus consists of this now−cooled material. The late stages of rifting were accompanied by voluminous mafic volcanism, that resulted in numerous dikes and sills now exposed all along the east coast (e.g. the Palisades Sill in NY) and the seismically detected "seaward dipping reflectors" at sea (Sawyer et al. 1992). The initial stages of sea−floor spreading may have involved significant along−axis flow of asthenospheric material (Gao et al, 1997; Vauchez et al, 1999). Evidence of such flow may be preserved in the mantle lithosphere near the continental margin.

Seismic velocity heterogeneity and the New England Anomaly. Seismic velocity under the cratonic North America is systematically faster than the global average, with the maximum of about 6% occurring in the Great Lakes region (e.g., Grand 1987). Velocities under the eastern North American margin are lower, but the overall pattern is not (as one might expect) margin−parallel. Instead, several smaller−scale (on the order of 400 km) but large amplitude (+/−6%) heterogeneities are present, some of which are elongate and near−perpendicular to the margin (Van der Lee and Nolet, 1997) (Figure 1). Regional P wave, S wave and surface wave tomographic studies show that this heterogeneity persists at smaller scales as well (Taylor and Toksoz, 1979; Levin et al, 1995; Levin et al., 2000a,b; A. Li, personal communication, 2000). Interestingly, the high level of velocity heterogeneity has no corresponding analog in the pattern of shear wave splitting, which is laterally homogeneous (Levin et al, 1999; Levin et al., 2000). The velocity heterogeneity must therefore represent "non−directional" aspects of the mantle structure (composition and/or temperature, not anisotropy).

The most prominent of the margin−perpendicular anomalies is a low velocity streak that Van der Lee and Nolet (1997) map as extending from beneath the NY Adirondack mountains, across New England, to a point at least 1000 km off shore (Figure 2). Its width is variable, but in the 200−500 km range. It is centered at a depth interval of about 100 km beneath the Adirondacks, deepening to 150 beneath the Atlantic (see Van der Lee and Nolet, 1997, their Plates 4 and 5). This "landward shallowing" of the asthenosphere − opposite from what one would normally expect at a continental margin − has been verified by Menke and Levin (2001) using differential array measurements of Rayleigh waves. The geographical location of the anomaly is roughly coincident with the track of the New England plume, leading van der Lee and Nolet (1997) to postulate that it represents a groove eroded into the lithosphere by the passage of that hot spot. This anomaly, which we will subsequently refer to as the "New England Anomaly" (NEA), is also evident in Levin et al.’s (2000) shear wave tomography (see Figure 2) and in Li’s (personal communication, 2000) maps of Rayleigh wave phase velocity (although there is only poor agreement on its exact shape).

Seismic Anisotropy and what it may represent. Seismological observations of lattice preferred orientation (LPO) of mantle olivine, made using shear wave splitting, indicate that the fabric of the mantle near the continental margin differs substantially from that of the central craton (Barruol et al. 1997, Fouch et al.

2000). When modeled as as single anisotropic layer, the margin has been shown to have an east−west fabric (i.e. shear wave fast direction), different than the northeasterly−southwesterly of the craton. The fabric of the central craton has been shown to correlate well with predicted patterns of mantle flow (Fouch et al. 2000) and with regional trends in geological features (Silver, 1996).

Two different interpretations have been put forward for the difference in fabric from craton to margin. Fouch et al. (2000) models the difference as being due to flow of the asthenosphere around an indentation in the craton. Levin et al. (1999, 2000a,b) argue that the fabric near the margin results from the superposition of two distinct anisotropic layers: an upper layer with a fabric that is locally perpendicular to the Appalachians and a lower layer that is oblique to the cratonic edge. They interpret the upper layer as mantle lithosphere, and the lower layer as asthenosphere. The upper layer underlies the Grenville, Appalachian and Avalon terranes, suggesting that it was formed by a single shearing event that postdates the assembly of these terranes e.g. a delamination of the lithospheric root during the final stages of the closure of the Iapetus (Levin et al, 2000a).

Although different, both Fouch et al.'s (2000) and Levin et al.'s (1999, 2000a) model involve a near−margin process that modifies the fabric of the central craton. The length scale over which this process has operated is not yet clear, as only a few seismic stations have been used to define the spatial distribution of the fabrics, with none in transitional regions. The fabric within New York and southern New England is suprisingly uniform, suggesting that the transition is located nearer to the craton in southern Canada.

Discontinuities in the lithospheric mantle and the depth of geology? The presence of seismic velocity discontinuities in the uppermost part of the subcrustal mantle characterizes stable continental regions (Fuchs and Vinnik, 1982; Pavlenkova, 1996). Some features, like the Hales discontinuity (first identified as a widespread feature in North America by Hales, 1969) and the Lehmann discontinuity (Lehman, 1960), have been observed under oceans as well (Revenaugh and Jordan, 1991).

A recent re−interpretation of data from the QUARTZ refraction profile (with nuclear explosion sources, crossing most of Eurasia) by (Morozova et al., 2000) presents an image of significantly laminated upper mantle. Support may be found in the image for most of the commonly reported mid−tectospheric interfaces, like the Hales (H) (Hales, 1969), the N (Pavlenkova, 1996), the "8−degree" (Thybo and Perhuch, 1997), and the Lehman (L) (Lehmann, 1960). Notably, the depth of these interfaces changes along the profile. Also, additional instances of velocity layering are inferred (e.g., a top of the low velocity zone at ~ 200 km depth) that are not associated with a named feature.

The nature of these discontinuities is a subject of active research, with phase transitions, composition changes, rheology differences, partial−melting accumulation and anisotropy all being offered as explanations (Hales, 1969; Fuchs, 1983; Benz and McCarthy, 1994; Bostock, 1997; Pavlenkova, 1996; Thybo and Perhuch, 1997; Levin and Park, 2000). Identifying these features and constraining their provenance and behavior throughout the eastern North America should help in resolving some of these issues. For instance, if Hales discontinuity represents slivers of ancient oceanic crust placed within the body of the continent during its assembly (Bostock, 1998), it should be discontinuous across the independently accreted blocks of the margin. If Lehman discontinuity marks the bottom of the consolidated mantle lithosphere (Gaherty and Jordan, 1995), it should should get shallower towards the coast, and will likely be disrupted by the NEA. On the other hand, if it marks the change in anisotropy−formation regime (Karato, 1992), the depth of L will be less dependent on the presence of the tectosphere.

Questions to Be Answered & Hypotheses to be Tested

1. Can unambiguous **lithospheric thinning**, as might have occurred during a Paleozoic delamination event or a Mesozoic rifting event, be detected?

Both kinds of events have been hypothesized to have occurred in this region, and both would have had profound effects on the thickness of the lithosphere. The existing data indicate that the margin is thinner than the craton, but cannot distinguish true strain−induced thinning from an apparent thinning due to the juxtaposition of terranes of different thickness. Nor does the existing data quantify any clear margin−perpendicular gradient in thickness within the Appalachian orogen. Quantification of both the amount of thinning and its lateral distribution is extremely important. Rifting is the better understood of the two processes, with clear evidence from the thermal subsidence (Steckler and Watts, 1978) that the strain is localized within ~100 km of the rift. It should thus affect only the extreme eastern edge of our study region. The pattern of thinning caused by a lithospheric delamination is largely unknown, and depends strongly on how that processes is modeled. In the extreme case of delamination by the sinking of a single large blob, the thinning might have a circular pattern (cf. Seber et al., 1996). Multiple thinning episodes are possible given the tectonic history of the region.

Any of the following features, imaged by our proposed higher resolution study of lithospheric structure, might be diagnostic of "true" lithospheric thinning: systematic dip of isovelocity surfaces and sub−horizontal discontinuities away from the margin; systematic increase in the strength of anisotropy fabric towards the margin; and internal reflectors crossing terranes (i.e. shear zones that cross terrane boundaries).

2. Are **lithospheric discontinuities**, such as the Hales (a.k.a. 80−km) discontinuity, present, and how are they distributed geographically?

   Sub−horizontal lithospheric discontinuties appear to be ubiquitous in stable continents, but their attributes (depth, strength, sense of property change etc.) are hardly uniform. Consequently, explanations for the origin of discontinuities within the uppermost mantle vary widely, including petrologic and rheologic transitions, anisotropy from localized shear zones, and zones of partial melt concentration. The issue of the origin of lithospehric mantle stratification is thus closely connected with the question of how the continental lithosphere is built up. Northeastern North America provides an ideal testing ground for these hypotheses. With no present−day tectonic activity, the lithosphere of this passive margin is a "finished product" of continental evolution. The sequence, timing, strike and areal extent of major tectonic events that shaped this region are known. All this should simplify the task of interpeting subtle seismic features in the upper−most mantle. The combination of seismological techniques that we will employ (surface wave studies for velocity distribution and receiver functions for discontinuity properties) will constrain not only the depth of discontinuities, but their thickness and anisotropic fabric (see example in Figure 5). Putting these findings into the nuanced context of regional tectonic history would considerably improve our understanding of causes for mantle lithospheric lamination.

3. What is the origin of the **New England Anomaly**? The NEA is a startling and unexpected feature for a passive continental margin: the velocity contrast is as large as between the craton and the tectonically−active western North America, and its strike is almost normal to the margin and the main tectonic units. It has no manifestation in the gravity field, nor is it associated with a heat flow anomaly, so it does not appear to represent a present−day tectonic process. One hypothesis that would seem to fit the facts is that it represents some sort of cut (a.k.a. "divot") in the original lithosphere. The shear wave velocity anomaly might then represent chemical differences between the original lithosphere and a younger replacement. Alternatively, small−scale asthenospheric flow into the cut might sustain a thermal anomaly. The juxtaposition of the NEA with the track of New England plume invites the hypothesis of a genetic relationship. However, the most recent theoretical studies (Ribe and Christensen, 1994; Cserepes, et al. 2000) indicate that plumes probably have only a weak ability to erode the lithosphere. Our primary goal is to understand the origin of this feature, and whether it represents a lithospheric modification process of general importance. A fundamental part of this issue

is understanding why the shear wave velocities are low − that is, whether they arise from **chemical** or **thermal** heterogeneties (previous studies seem to rule out anistropic heterogeneties). Measurements of attenuation and compressional to shear wave velocity ratios can discriminate between the two. Another fundamental issue is whether the anomaly represents a true cut in the lithosphere. Disruptions in regional lithospheric discontinuities would favor such an interpretation, as would high velocity sidelobes, caused by mantle depletion, as occur around the Yellowstone hotspot (Saltzer and Humphreys, 2001). Finally, only a narrow anomaly with a strike that is within a few degrees of the New England plume track would be consistent with their genetic association.

Proposed Research

The project aims at assembling, for the first time, a two−dimensional seismometric dataset, extending from the North American craton eastward through the continental margin, with coverage appropriate for addressing issues of continental structure and evolution. Studies with similar coverage have targeted numerous regions in the tectonically−active western part of the North American continent, in Europe and Africa (e.g. the Kaapval project), and invariably yielded exciting discoveries. Our proposed project is one of the first to target a passive margin. The low cost at which excellent aerial coverage may be obtained adds motivation for this study.

As Figure 2 illustrates, considerable amount of broadband seismic data is recorded presently by permanent broad−band observatories in a swath along the Atlantic margin from Delaware to New England, extending inland to the Great Lakes. These stations will soon be supplemented by the POLARIS network (see http://www.polarisnet.ca/index.html) in southeastern Canada. POLARIS is expected to operate for 4 years, with real−time data acquisition and open data access (M. Bostock, personal communication, 2001). Additionaly, a number of portable experiments of 1 year or longer duration have been carried out (e.g. MOMA, ABBA, NOMAD), with data mostly available via IRIS DMC.

A wide gap in observational coverage remains in the part of Northern Appalachians critical to resolving many of the questions we would like to address − between St. Lawrence river and the Atlantic coast. We propose to close this gap with a portable deployment of 6 seismic observatories in Maine, St. Lawrence and New Brunswick (see Figure 1). A two−year duration of the proposed project should yield enough data for exploring directional dependence of anisotropy−sensitive observables (receiver functions, shear wave splitting). Combined data from the proposed deployment and from other permanent stations, especially the POLARIS net, will provide a dataset for tomographic imaging of the Northern Appalachian region with resolution ~100 km − a big improvement to that presently possible.

The project will thus be composed of two parallel tasks: 1) A portable deployment of 6 seismic observatories for 2 years, to collect new data, and 2) a synthesis effort to merge all available data and to interpret it jointly.

Task 1) will require identification of 6 suitable sites (secure, quiet and with AC power), construction of low−tech enclosures, and periodic visits to retrieve data via a disk swap. We have operated similar networks of portable seismic obsevatories in Iceland (Menke), Kamchatka (Levin) and the Northeastern North America (both), and are familiar with relevant issues. In addition, we will utilize technical expertise of LDEO regional network operators during the deployment setup. Close proximity of the region to LDEO simplifies the logistics. All distances involved are drivable. Locating portable observatories on private properties ensures security, availability of power and easy access, and is generally not a problem in the region. The task of archiving acquired data will be performed using a dedicated workstation that we will request from PASSCAL.

Task 2) is generally facilitated by IRIS DMC (for global, US national and some Canadian stations) and data archives of LCSN (see http://www.ldeo.columbia.edu/LCSN/). Continuous waveform data from the Canadian national network is available via an automatic data retrieval mechanism (see http://www.seismo.NRCan.gc.ca). Through our previous experience with a similar project (see "Prior Support") we are cognizant of complications that may arise (data timing, sensor calibration etc.)

The data analysis will be performed concurrently with the new data collection, starting with already−archived data from existing stations, and will be extended to the new data as it arrives. The following "seismological products" will be prepared: **Receiver functions** (both radial and transverse) for all stations; **shear wave splitting** measurements (under both 1−layer and multilayer assumptions) for all stations; **Surface wave tomography;** and **Body wave** velocity and attenuation tomography; In addition, we will perform specialized analysis of Love−Rayleigh coupling, polarization, etc. as is warranted by features in the data.

Methods

Surface Wave Studies

Estimates of shear wave velocity variation with depth can be obtained in a standard way by inverting the regionally−localized, frequency−dependent phase velocity of fundamental−mode Rayleigh waves. Phase velocity localization will be performed using an estimation technique similar to the one popularized by Forsyth, in which the phase velocity is perturbed so as to match the evolution of the Rayleigh waveform across the array. This method provides a natural way of including the effect of both anisotropy and multipathing (which is sometimes present at the shorter periods).

The tomographic inversions will be supplemented by "point" estimates of phase velocity velocity and azimuth of propagation made with 3−station triangular sub−arrays (Menke and Levin, in press, 2001) (Figure 3). This method allows us to test some of the assumptions used in the tomography (e.g. that the surface waves propagate along the great circle connecting source and receiver). It also provides measurents of the azimuthal variations of phase velocity (as may be cause by anisotropy or diping structures) that are uneffected by of any trade−offs inherent in the tomographic reconstruction.

Surface waves observed by the array will be analyzed for the presence of mode−converted phases, e.g. quasi−Love waves (Park and Yu, 1993; Yu and Park, 1994). Observations of quasi−Love provide strong spatial constraints on the location of regions where abrupt changes in anisotropic properties occur (Yu et al., 1995; Levin and Park, 1998b), while their spectrum contains information on the depth provenance of the anisotropic features.

Finally, horizontal−component seismograms will be used to measure the frequency−dependent azimuth of particle motion. This measurement compliments the azimuth measurements made using the triangular array method, and will be used to detect the lateral refraction of the surface waves by heterogeneities.

Body Wave Tomography Traveltimes of compressional and shear body waves, and attenuation of shear waves, will be used in first−order tomographic imaging. We expect large variation of seismic velocity field along the array as it goes from the craton across the passive rifted margin. Current compressional wave tomography is limited to We hope to provide significant refinement to the currently available images of upper−mantle velocity field, in particular where the width of transition regions is concerned. We do not know whether detectable variations in attenuation are present, but any negative correlation with shear wave velocity would strongly suggest that heterogenity was temperature−driven.

We have prior experience using velocity and attenuation tomography imaging methods on smaller datasets from the New York, southern New England and Iceland. We are confident that the improved dataset can achieve ~100 km resolution across the entire proposed array. Menke’s publicaly−distributed RAYTRACE3D code (ftp://ftp.ldeo.columbia.edu/pub/menke/raytrace3d.tar.Z) will be used for these inversions.

Receiver Function Analysis Isolation and analysis of P−S mode−converted phases within the coda of teleseismic body waves − the so−called receiver function (RF) method − is best known for its ability to probe for the presence of sub−horizontal interfaces of the lithosphere. However, recent work has also brought forward it ability to detect anisotropy, especially when the usual Radial−component receiver functions are complemented by Transverse−component functions (Levin & Park, 1997b, 1998a; Bostock 1997, 1998). These functions have proved extremely useful in constraining the depth of mantle LPO in other parts of the world (Levin & Park 1997, 2000a) (figure 5).

Use of recently developed multitaper spectral coherence estimator (Park & Levin, 2000) leads to considerable improvement in the resolving power of the receiver function technique. Experience of using this new tool on data sets from stable continental regions is particularly encouraging. In the Arabian shield a clear evidence for the Hales discontinuity is found, and shear deformation associated with it is inferred on the basis of careful analysis of backazimuth−dependent receiver functions (Levin & Park, 2000a). Of particular value is the ability of the algorithm to combine contributions from sources at virtually any distances. The spectral coherence RF−estimation technique can analyze the high frequency energy in both core phases and regional seismic waves, offering improved vertical resolution of interfaces like the Moho, Hales and Lehmann discontinuities.

Our experience of working with transversely polarized receiver functions should help us overcome a problem of multiply−converted phases obscuring energy from features in the lower part of mantle lithosphere. As noted by Bostock (1997), multiples are typically present in the SV−polarized component of the receiver function, and thus use of SH−polarized (transverse) receiver functions is key to studies of upper−mantle structure in 100−200 km depth range. We successfully utilized tranverse RFs to study subcrustal mantle under the east coast of Kamchatka where radial receiver functions are dominated by near−surface reverberations (Levin et al., 2001). The spacing of observing sites is dense enough in a few areas of the region (e.g., in Adirondack Mountains) to explore the advantages of migrating receiver functions (e.g., Duecker and Sheehan, 1997). We do not expect this to be practical over the whole region as the station spacing is too sparse for the depth range (upper 250 km) we will concentrate on.

Shear Wave Splitting In their previous collaborative effort PI’s Menke and Levin performed joint analysis of shear wave splitting and traveltime delays in the New York and New England region (Levin et al. 1999, Levin et al. 2000ab; see also Prior Results). This analysis stressed the importance of determining, for a given station, the dependence of apparent splitting direction on the arrival direction of the SKS waves (Figure 4). This directional dependence is key to detecting layers with distinct anisotropic properties. Results of these previous studies motivate this proposal.

The PI’s have developed both a data analysis technique capable of making apparent splitting direction measurements from single SKS phases,

ftp://ftp.ldeo.columbia.edu/pub/menke/ah_splitest2.tar.Z

and a modeling method capable of determining the anisotropic parameters from the observations,

ftp://ftp.ldeo.columbia.edu/pub/menke/SPLITTING_MODELER.tar.Z

This methodology is also capable of detecting and modeling the effect of several distinct layers of anisotropy (i.e. at several depths), should any be present.

Management Plan

Both PI’s will broadly participate in all phases of the project. Levin, with significant experience in previous PASSCAL array efforts, will lead the array deployment. Once the data is collected, Menke will lead the surface wave analysis and tomographic imaging effort and Levin will lead the receiver function and splitting analysis.

Use of Facilities

LDEO will commit six of its broadband seismometers to the first year of the data collection project, with the expectation that up to 5 of them can be swapped out for IRIS/PASSCAL instrumentation thereafter. The idea is to provide a quick startup to the field program, irrespective of IRIS's tight instrument schedule. The LDEO equipment is shared amongst all the members of the LDEO Seismology group, and is needed elsewhere for earthquake aftershock studies thereafter.

Dissemination of Results

We will submit PASSCAL data to the IRIS DMC within one year of its collection, and to any other public archives that are required by any other facilities involved. We will maintain archives of data and preliminary results on our institutional web sites (as we now do for previous studies, see for example http://www.ldeo.columbia.edu/user/menke). We will present results at scientific national meetings, such as the Fall AGU, and make a best−faith effort to publish them rapidly in a peer−reviewed journal.

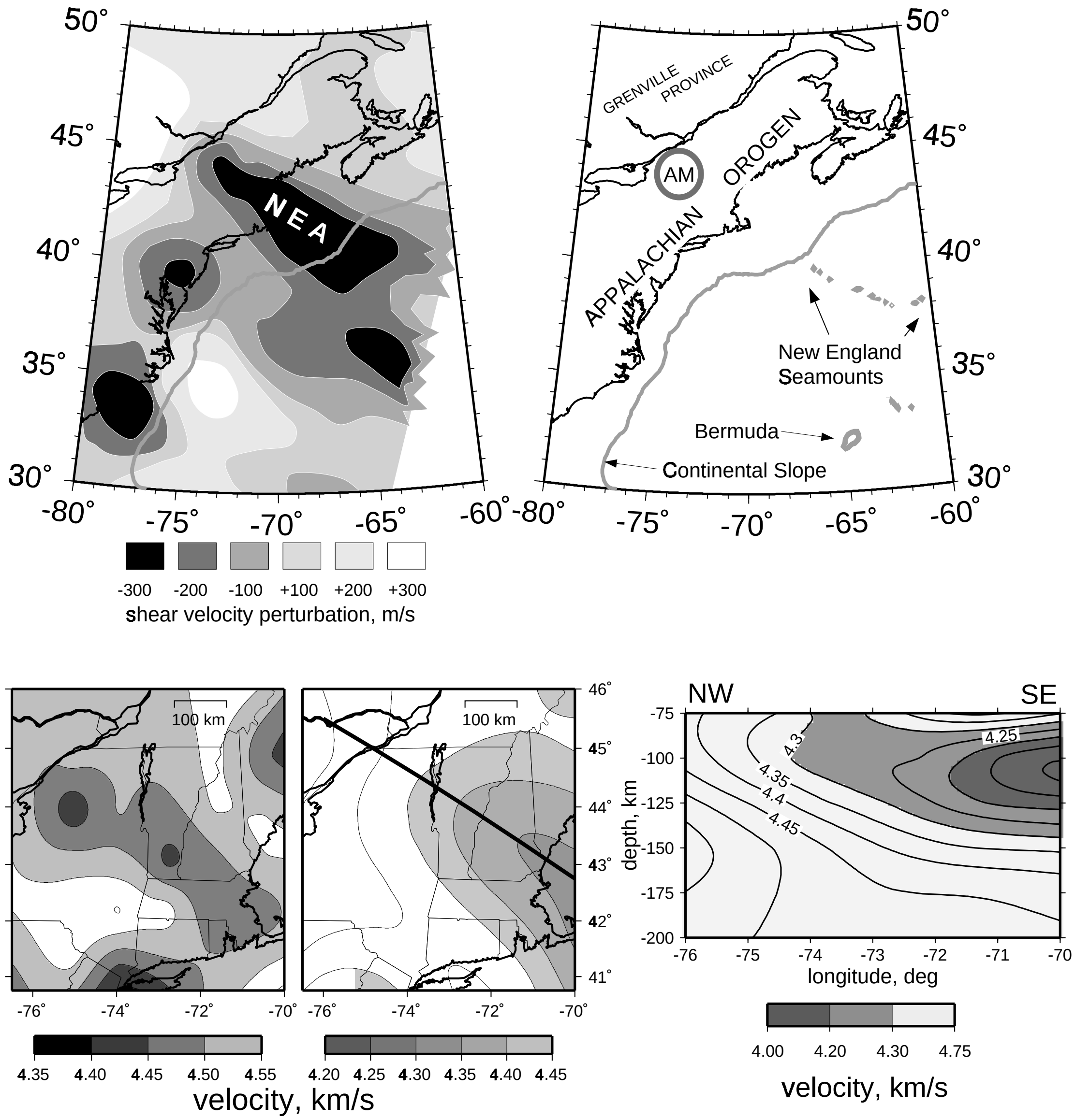

Figure 1. *UPPER LEFT* Shear wave velocity anomalies 100 km beneath the eastern North America passive margin (adapted from Van der Lee and Nolet, 1997). *UPPER RIGHT*: Tectonic units of the eastern North America passive margin. A depth contour of 2000m (shaded) outlines the edge of the continent. AM - Adirondack Mountains.

LOWER PANEL Regional variations in shear wave speed at 150 km depth, as imaged by body wave tomography with S and SKS waves (*Levin et al*., 1999) (left) and Raleigh wave tomography (*Van der Lee and Nolet*, 1997) (middle). Solid line on the middle panel indicates the trace of the crossection shown at right. There is a general aggreement in the trend of the low velocity features despite large differences in sampling and vastly disparate scales of these studies (body waves - the region shown, Rayleigh waves - continent-wide). Note an "uplift" of velocity contours towards the interior of the craton.

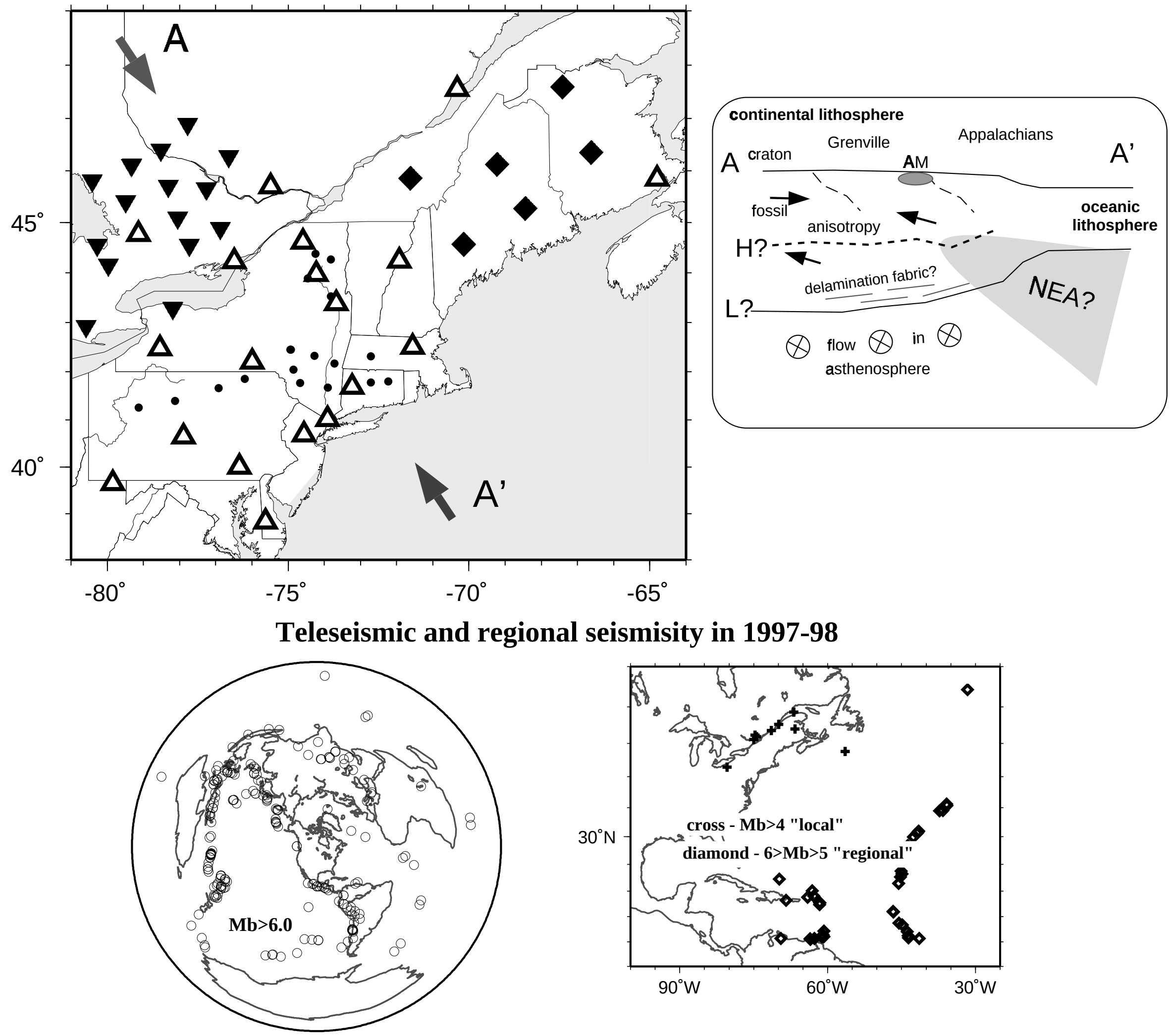

Figure 2. TopRight: Seismic observatories in the region: permanent stations (open triangles), portable stations with over 1 year of data (dots), POLARIS array (solid triangles). Proposed portable deployment is shown with diamonds. Sites are tentative. TopLeft: Schematic cartoon of subsurface features we seek to identify and explore, drawn (not to scale) along the line A-A'.
AM - Adirondack Mountains; NEA - New England Anomaly (low seismic velocities); H, L - Hales and Lehman discontinuities.
Bottom panels illustrate distribution of seismic sources in a 2-year period that will form the dataset for tomographic imaging of the region, and for waveform analysis at portable netwrok sites.

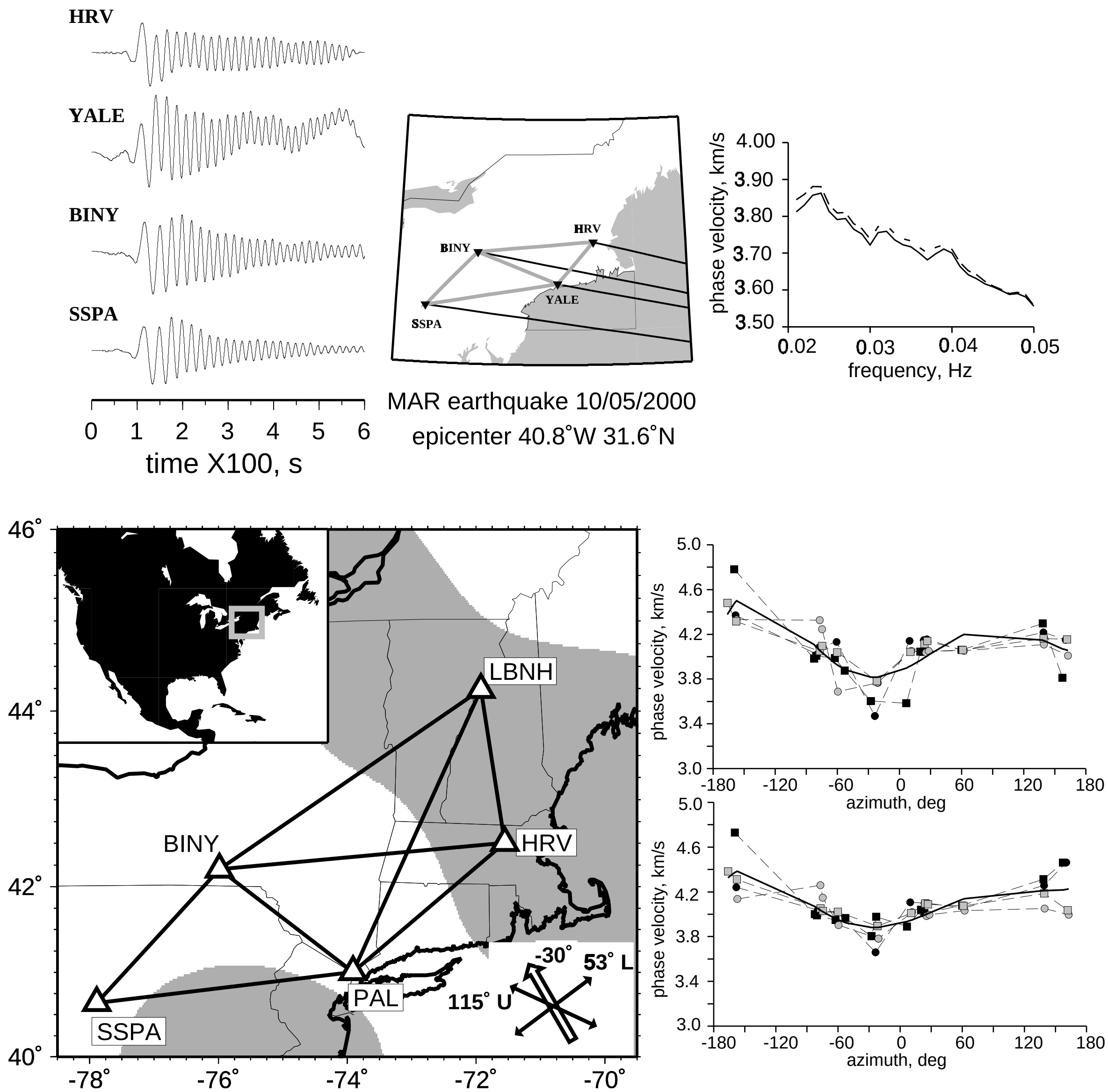

Figure 3. *UPPER PANEL (left)* Well-dispersed Raleigh wave from a Mid-Atlantic Ridge earthquake observed on four vertical-componen broadband stations in Northeastern US. *(middle)* Map showing four stations (HRV, YALE, BING, SSPA), which define southern and northern trianges. *(right)* Local estimate of phase velocity for each triangle, computed with the differential phase method. Note that the northern triangle (solid curve) has systematically lower velocities. *LOWER PANEL (left)* Map of broadband seismic stations (triangles) in northeastern US grouped into four triangular three-station arrays that are used to make local measurements of Rayleigh wave phase velocity, as follows: (T1) PAL-BINY-HRV; (T2) PAL-SSPA-BINY; (T3) PAL-HRV-LBNH; (T4) BINY-HRV-LBNH. Shading shows an area of NA95 model (*Van der Lee and Nolet*, 1997) where shear wave velocity is below 4.35 km/s at 100 km depth. Orientations of anisotropic symmetry axes in two layers of mantle fabric (*Levin et al.*, 1999) are shown by solid arrows (U - upper; L - lower). An open arrow shows the shallowing of the lithosphere-asthenosphere boundary towards 30 deg NW inferred in this study (*Menke and Levin*, 2001). *(right)* Variation of the average phase velocity with azimuth for four trianges, in the 75-100 s period range (upper plot) and 35-50 s period range (lower plot). Each symbol represents a single earthquake observed on a single triangle of stations (black circles, T1; black squares, T2; grey circles, T3; grey squares, T4; see Figure 3 for triangle definitions). The bold curve is a smooth polynomail fit to all the data.

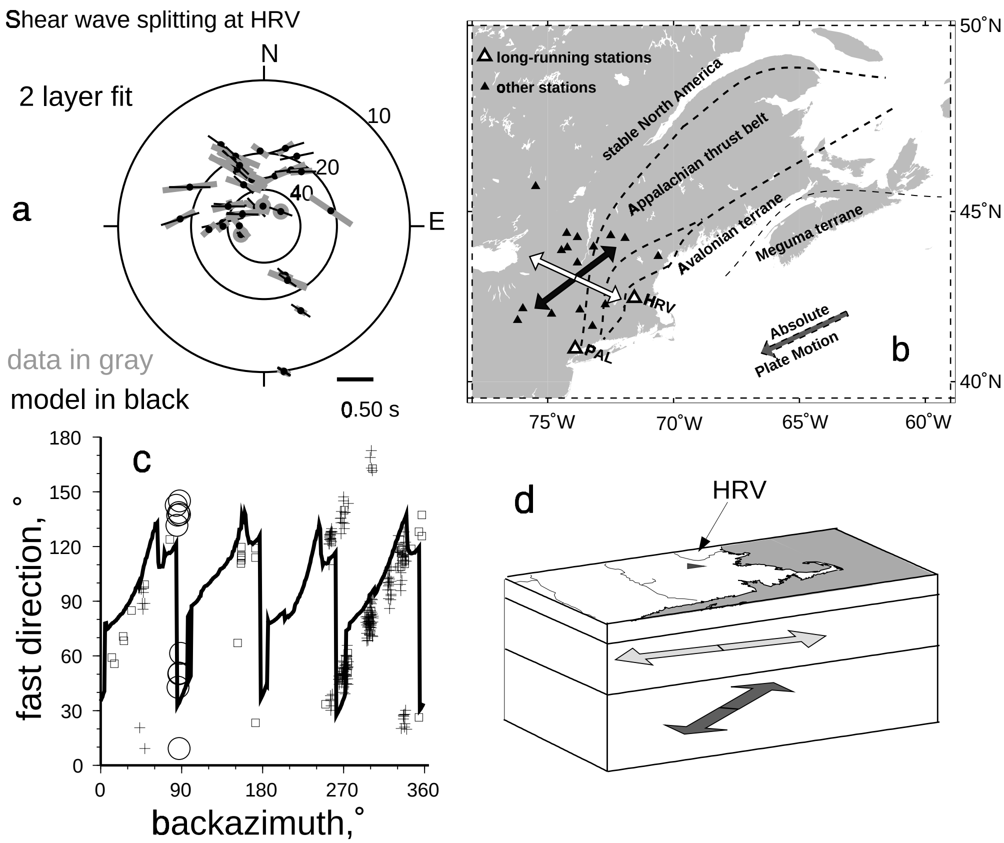

Figure 4 a) Observed (solid) and predicted (shaded) shear wave splitting data for HRV (Harvard, MA). Splitting values are shown as bars centered on the nominal back azimuth and apparent velocity (from IASPEI91 velocity model). The bar orientation parallels the azimuth φ of the fast direction. Bar length is proportional to the time delay τ. Near-zero splitting delays are plotted with open circles. b) Map of station network. Major tectonic boundaries for the Northern Appalachian orogen are indicated. 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. c) Observed and predicted variation of the apparent fast direction of the shear wave speed. Data for all stations shown in b) observed during the spring and summer of 1995 are shown by crosses. Solid line shows a pattern of fast direction values predicted by the two-layer model for HRV built using a different data set (squares). Splitting values measured from October, 2000 event near lake Tanganyika (backazimuth right on the node of the pattern) are shown by large circles. d) Schematic diagram showing orientation of anisotropic axes in the two-layer model.

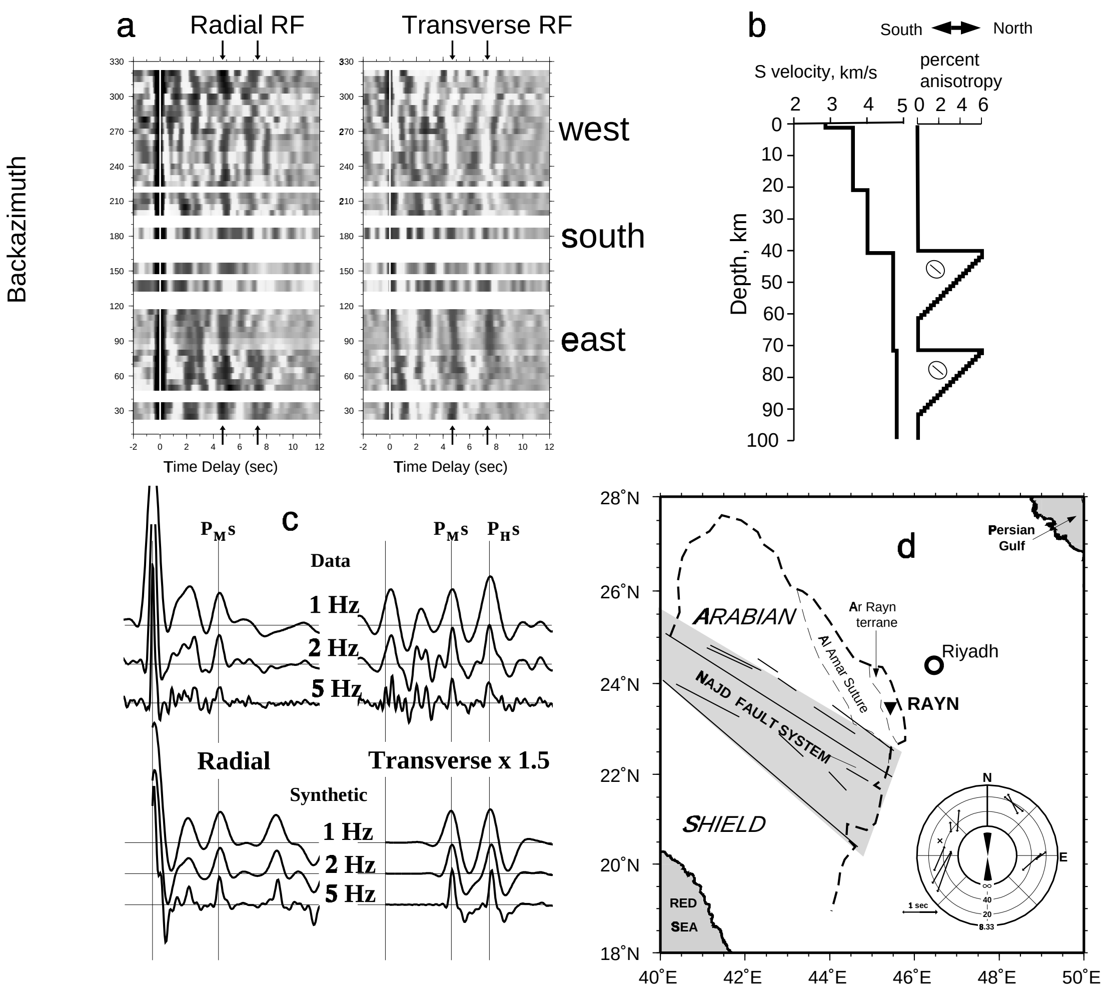

Figure 5 Example of function analisys for upper-mantle discontinuity structure. a) Receiver functions (RFs) computed for RAYN (Ar-Rayn, Saudi Arabia) presented as a function of backazimuth. Upward motion is dark, downward motion is light. Data used include direct P, PKP and P*diff* phases observed between spring of 1997 and summer of 1999. RF spectra are limited at 1 Hz. Phases PMs and PHs are identified by arrows. Note the polarity changes in the transverse RFs between eastern and western directions. b) Vertical profile of S wave velocity and anisotropy for the best-fitting model. WIthin both anisotropic regions the symmetry axis is oriented N-S, and tilted ~50° from the vertical. c) data (RFs stacked in backazimuth range 75° -107°) and reflectivity synthetics (baz 90°, phase velocity 20 s/km) computed in best-fitting model. d) Indicators of anisotropy (inset) in regional tectonic framework. Shear-wave splitting observations are plotted as a function of backazimuth and phase velocity. The arrows are aligned with the fast direction and scaled with the splitting delay. The center of the polar plot shows the range of possible orientations for anisotropic fast-axis strike within two upper-mantle zones identified through RF analysis. Note disagreement between anisotropy orientations inferred from RFs and SKS phases arriving from the East. This signifies either lateral heterogeneity or vertical stratification of rock texture in the uppermost mantle.