Results from Prior NSF Support

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

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The purpose of this research was to test the proposition that the mantle beneath northeastern North America 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 terrains (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 the past 5 years. 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 terrains 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.**, Vol. 105 , No. B8 , p. 19,029, 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/

This is a proposal to collect new data on the structure of the lithosphere and underlying asthenosphere across the passive margin of eastern North America, and to use these data to gain new insights into both the continental accretion and continental rifting processes. The target is primarily the upper mantle (as contrasted to the crust). Our motivation is that deformation in the mantle is a key element of both processes, but that good structural data bearing on that deformation is currently lacking, especially at the characteristic length scales of 250 km and less. Key parts of the new data collection effort are offshore observations made with long-deployment ocean bottom sensors (OBS's). Our contention is that data from both the landward and the seaward side of the margin are needed to constrain the details of its structure. We assert that the significance of a given structural feature can only be properly interpreted when one knows how it behaves across the margin.

Background

The northeastern edge of North America is a "textbook-case" passive margin (Grow and Sheridan, 1988; Sheridan et al., 1995). 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 (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. Of particular interest in the context of this proposal 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).

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 thicknesses, 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 Lee and Nolet, 1997). A recent study by Li et al. (personal communication, 2000), using MOMA data, provide further evidence of this thinning. Cratonic North America is systematically faster than average, with the maximum of about 6% occurring in the Ontario/Great Lakes States region The Northeastern North American margin is systematically slow, but the overall pattern is not (as one might expect) margin-parallel. Instead, it consists of a set of smaller-scale (<400 km) but large amplitude (+/- 6%) heterogeneities, many of which are elongate and which trend sub-perpendicular the margin.

One of these heterogeneities (a slow, NW-SE trending streak; see Figure 1) starts beneath the

NY Adirondacks, crosses New Hampshire and appears to extend about 1000 km offshore. Regional P wave, S wave and surface wave tomographic studies using land stations have confirmed that the western, continental portion of this low velocity streak exists (Levin et al, 1995; Levin et al. 2000b; A. Li, personal communication, 2000), although they also indicate that it has considerable small scale (100 km) structure not evident in the van der Lee and Nolet image. Furthermore, it has no corresponding analog in the pattern of shear wave splitting, and thus represents chemical (or thermal) heterogeneity (as contrasted to apparent heterogeneity cased by "anisotropic domains" of different orientation). While we have no particular reason to disbelieve the eastern, sub-oceanic portion, we note that it occurs at the eastern edge of van der Lee and Nolet image, where resolution is presumably the poorest.

The significance of the New England and other streaks is not well understood. The New England streak, in particular, has been associated with the hot spot that made the New England sea mounts at 0.1 Ga. The western, continental part of the streak can then be understood as a place where fast cratonic lithosphere was eroded away and replaced by slower material. This interpretation, however, has more trouble explaining why sub-oceanic part of the streak is slow, since one would imagine that replacing oceanic lithosphere with more depleted plume-derived asthenosphere would lead to a fast anomaly (note that the thermal signature would have dissipated). Indeed, one of the fast streaks, near the Bahamas, is in a place said to be influenced by a hot spot.

A hot spot explanation is only one possibiltiy among many, of course. Another possibiltiy is that the anomalies are purely continental, and represent a signal associated with delamination of pods of an originally thicker continental lithosphere during the Appalachian Orogeny (Levin et al., 2000a). Still another is that they are somehow related to segmentation of the Mid Atlantic Ridge during the early phase of Mesozoic rifting. The issue of whether the streaks actually cross the ocean/continent boundary, and the details of their shape, is thus of considerable importance.

Estimates of the vertical dimensions of the lithosphere under the eastern part of the North American plate 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, atleast for the southern part of the craton sampled that was sampled by the MOMO array. A follow-up study by Li et al. (personal communication, 2000), also using MOMA data, shows an interface at 280 km, deepening to the west, that may be the base of the lithosphere.

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 just seaward of the continental margin.

Seismological observations of lattice preferred orientation (LPO) of mantle olivine, made using shear wave splitting, indicate that there are two distinct layers of mantle "fabric" that are more-or-less uniform across much of northeastern North America (Figure 2) (Levin et al., 1999, 2000b). If 6% anisotropy is assumed, these layers are modeled to be 60 and 90 km thick, and would be thicker if the anisotropy were weaker. The upper layer has an anisotropic fast-axis (N115E) locally perpendicular to the Appalachians, oblique to the cratonic edge (Figure 2). The lower layer has an anisotropic fast axis of S53W that is sub-parallel to both the continental margin and to the S65W absolute motion of the North American plate. The actual depth of these layers has not been directly determined, except insofar as they must be above the transition zone (410 km) if caused by olivine LPO. However, the upper layer has been interpreted as being in the mantle lithosphere, and the lower layer in the mantle 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). The lower layer has been interpreted as being associated with asthenospheric flow. Further to the west seismic anisotropy has been shown to correlate well with predicted patterns of mantle flow (Fouch et al. 2000), but also to be consistent with regional trends in geological features (Silver, 1996). It is likely that one or both of the anisotropic layers identified close to the coast disappear under the central parts of the craton. However, since many of the analyses assumed a single LPO layer, this interpretation needs to be further tested.

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, have been observed under oceans as well (Revenaugh and Jordan, 1991). The nature of these discontinuities is a subject of active research, with phase transitions, composition changes and anisotropy all being offered as explanations (see Bostock, 1997; 1998; and Levin & Park 2000 for a review). Identifying these features and constraining their provenance and behavior across the continental margin 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), we wouldn't expect to find it under the ocean.

Questions to be answered and Hypotheses to be Tested

1. How smooth are changes in the properties of the lithosphere across major structural boundaries, such as the between the Archean craton, Grenville and Appalachian terranes and the ocean? How intense are the heterogeneities? Can sub-vertical boundaries be detected? These questions bear upon the degree to which terranes with different provenance are altered during and after their accretion. Does the mantle beneath them still have distinct edges? Or has the mantle been smoothed out by processes such as delamination during an orogeny, as Levin et al. (2000a) hypothesize for the late Paleozoic? Tomographic inversions show a rather smooth lithosphere, but this is probably largely due to their low resolution (500 km). The new data will allow improved resolution.

2. Do the margin-perpendicular streaks, and especially the New England streak, cross the continent-ocean boundary? Where are they the most intense? What mechanisms are consistent with the details of their structure?

3. Is the continental mantle lithosphere really more heterogeneous than the oceanic lithosphere? Relatively little work has been done imaging the older, colder parts of the oceanic lithosphere (as contrasted to the intensively studied ridges, where the heterogenity is primarlity thermal).

4. Do the two mantle LPO layers thicken, thin or pinch out (or otherwise change in properties), either towards the center of the craton or in the Atlantic Ocean? The existing data, limited to NY and southern New England, show only minor regional variability of the layer thicknesses. Are different layers encountered? This is a straightforward question that can be answered by shear wave splitting measurements (see methods discussion, below) along the proposed array.

5. Is there any heterogeneity in the asthenospheric flow (i.e. the lower LPO layer) that might indicate that it is being controlled by drag from the continental keel? If so, the flow models of Fouch et al (2000) suggest that anisotropy should diminish away from the coast, over the ~1000 km length of the ocean part of the proposed array. Or does it continue unabated well seaward of the continental margin? In this later case it would likely be controlled by a large-scale coherent shear between the plate and return flow in the underlying asthenosphere.

6. Did the continental lithosphere neck during the Mesozoic rifting (as seems likely), and if so, over what length scale? Any such necking would, of course, be fossil. The present-day lithosphere includes both the upper, Precambrian/Paleozoic necked continental lithosphere, and a lower, younger Mesozoic lithosphere produced by cooling of the asthenosphere. Any shallowing (or interruption) of internal layers within the mantle across the margin would diagnose such necking. A sudden change in LPO with depth might also mark the boundary between old and young material. (The flow pattern of the asthenosphere that filled in necked region might well be different than the fabric of the older material above).

7. Is the upper LPO layer in the continental lithosphere? If this is the case, would would expect it to end at the continental margin. However, because the oceanic lithosphere is also likely to be anisotropic, with a spreading-parallel olivine fast direction that had a similar direction, the LPO layer may thicken across the margin. On the continent the top LPO layer represents a shear-wave splitting time of 0.75 s. Thus is considerably smaller than the up to 2 s reported for SKS observations in the oceans (Wolfe and Solomon, 1998).

8. Did along-axis mantle flow occur during the Mesozoic rifting? A narrow (50-100 km) zone with a margin-parallel LPO fast direction would diagnose such flow.

9. Can the interface between the two LPO layers, or other sub-horizontal interfaces within the mantle, be detected using receiver function analysis (see methods discussion, below)? The hypothesized change in anisotropy across the boundary suggests that transverse-component receiver functions might be particularly useful in this regard.

10. Does the lithosphere contain additional velocity interfaces below the crust-mantle transition (e.g., Hales discontinuity at ~80km, Lehmann discontinuity between 100 and 200 km)? Are these interfaces continuous across major tectonic boundaries within the continent (e.g. craton - Grenville), as might be expected if they were a simple phase boundary? Are they continuous across the continental - oceanic transition? If not - does oceanic lithosphere have its own layering pattern? What, once these questions are answered, can be said about the nature of mantle lithosphere layering?

New Data Collection Effort with Onshore/Offshore Array

We propose to perform an onshore-offshore passive seismic experiment that will use observations of distant and regional seismicity to characterize lithospheric structure.

The array is designed to probe the lithosphere across a region extending from Lake Superior in the interior of the Canadian craton to the North Atlantic abyssal plane near Bermuda, from as far south as Delaware to as far north as Nova Scotia. This region includes both the New England streak and the more normal part of the margin to its south. We will combine data from several distinct arrays (Figure 3), which total to about 100 seismic stations:

1. An array of 16 OBS's deployed for 15 months on the sea floor in a corridor between Bermuda and the continental shelf.
2. A temporary deployment of 10 PASSCAL stations, mostly along the Atlantic coast and on Bermuda.
3. The existing network of about 20 broadband seismic observatories in the Eastern US and Canada. The stations include the US National Seismic Network, Canadian Seismic Network and Global Seismic Network, the newly expanded Lamont Cooperative Seismic Network in New York and New England area, and miscellaneous other regional networks.
4. The new 25-station Canadian POLARIS array, which provides dense coverage in the cratonic region of southeastern Canada (http://www.cg.NRCan.gc.ca/polaris/).

As a result, station spacing within the array will be 100-200 km in the coastal and continental shelf region, and 200-300 km at both the "craton" and the "ocean" ends. An important aspect of this array will be that both land and sea stations will operate contemporaneously, thus permitting observations of the same set of earthquakes. This "synoptic" dataset will allow precise discrimination of structure effects from source effects.

PASSCAL Stations The land part of the array, 10 portable broadband seismic observatories from the PASSCAL pool, will be deployed during the first year of the project, and will continuously acquire data for 2 years. We will choose land sites complementary to the distribution of existing permanent seismic stations. An anticipated expansion of USNSN array, and scheduled expansion of Canadian seismic monitoring effort called POLARIS may result in a denser array. Our proposed deployment of a station in Bermuda might be unnecessary, should the US Geological Survey deploy its planned station there. In that event, we will instead deploy a station in central Maine.

Our plan calls for the operation of PASSCAL stations near the ocean, where noise levels are, of course, higher than at inland sites. In order to test the premise that we will nevertheless obtain a reasonable amount of good data, we operated a REFTEK/CMG40T broadband seismometer for one month each at two sites on Long Island, NY (one in the southwest at East Rockaway, NY, the other in the southeast, at East Hampton, NY). In both cases the sensors were placed on a concrete platform overlying sand. Although noise levels were somewhat higher than on hard rock, excellent data was nonetheless recorded (Figure 4). The East Rockaway, NY station recorded several core phases from western Pacific events that could be used to measure shear wave splitting directions. The splitting direction matches the previously-observed pattern for the NY/New England region, although the amplitude is somewhat smaller. The smaller amplitude, should it be observed for more data, would indicate a thinnging of the LPO layers towards the continental margin.

OBS Deployment We plan a 15 month deployment of 16 three-component instruments from the new OBS pool to begin during the first year of the project. These instruments have successfully recorded both regional and teleseismic data in many different settings, including the East Pacific Rise and Lau Basin. The work will require two 12-day cruises on an intermediate-class research vessel if the ports are Norfolk and Woods Hole (12 science days plus one day of transit if the ports are Norfolk and Woods Hole, or two days if they are Miami and Woods Hole).

The proposed deployment is longer in duration than the MELT experiment which yielded adequate shear wave splitting data and excellent Rayleigh wave observations. Recording conditions for this experiment should be greatly superior to MELT: the distribution of events is superior, attenuation should be much lower here than under the MELT EPR sites, and microseisms (seafloor noise levels) are expected to be 10 to 20 dB lower in amplitude and of higher frequency (thus providing a wider useful bandwidth for detection of long period arrivals). The instruments are sited off the shelf, in water deep enough to avoid strong ocean bottom currents. It is expected that some technique for burying OBS sensors in the mud will be developed in the near future. We would propose the 16th OBS site shown in the Gulf of Maine (light gray diamond in deployment figure) would be an ideal site to test such an installation. Placing sensors below the seabed isolates the sensors from tilt noise due to the action of currents, otherwise the site the in Gulf of Maine will be too noisy to be useful due to strong tidal currents.

We prefer to have both seismometer and differential pressure gauge (DPG) records from all the instruments. However, if seismometers are not available due to scheduling constraints we could use instruments equipped with only DPG's as the main tool to make broadband observations of P and Rayleigh waves. This sensor proved quite reliable on past experiments (e.g. the MELT experient), and will suffice for the main imaging component of this experiment. However, since we are also interested in anisotropy and receiver functions (which require measurements of the horizontal component of shear waves), we need to deploy 3-component seismometers on at least half of the instruments. We note that the performance of horizontal velocity sensors is admittedly poorer than is perhaps desired. Nevertheless, several investigators have succeeded in making useful measurements with them (e.g. Wolfe & Solomon 1998; Hung et al. 2000).

Use of existing data sets We will also take advantage of previously collected data sets in the proposed region of study, by permanent stations (e.g. USNSN nodes) as well as temporary (e.g. prior PASSCAL) deployments. By including these data sets in our study we will improve data density and duration of observations.

Data Sources Figure 2 illustrates the location of the proposed onshore/offshore array with respect to global seismicity exceeding Mb=6.0 in a two-year interval. We anticipate excellent data coverage from the northwest, west and southwest, more modest coverage from the northeast and east. In addition, we expect to record a number of smaller events from Mid-Atlantic Ridge and Caribbean Basin, which promises to fill the coverage gap. Local seismicity within and close to the array will be utilized as well.

Methods

Local Estimates of Surface Wave Phase Velocity Estimates of shear wave velocity variation with depth can be obtained using observations of phase velocity of fundamental surface waves on a triangular array. To facilitate this mode of analysis our OBS deployment is planned in triangular pattern. On land we should be able to form subarrays of various sizes, especially close to the Atlantic coast. By constraining vertical profiles of shear velocity for small segments of the array we will obtain additional constraints on the lateral variation of velocity.

We have made some test measurements of Rayleigh wave phase velocities (Figure 5) from a Mid Atlantic Ridge earthquake observed on four stations (Harvard, MA; New Haven (Yale), CT; Binghampton, NY and Standing Stone, PA.) The phase velocity estimated for the southern triangle of stations (Yale, Binghampton, Standing Stone) is (as expected) 1-2% faster than for the northern triangle (Yale, Binghampton, Harvard) over the 20-50 s period band. This band is one in which Li's work shows significant lateral heterogeneity.

Surface Wave Mode conversion 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. Since the diagnostic quasi-Love phase has P-SV motion, the DSP's on the ocean-bottom instruments will be able to record them.

Shear Wave Splitting In their previous collaborative effort PI's Menke, Park 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 2). This directional dependence is key to detecting layers with distinct anisotropic properties.

In the previously studied NY-New England region, the presence of the two LPO layers caused the splitting direction to vary rapidly with backazimuth, even for the limited backazimuth range subtended by the subduction zones of the western Pacific (which are seismically very active). So even though the proposed array deployment - and especially the OBS part - has a limited duration, we expect to be able to distinguish regions with the same two LPO layers from, say, regions in which there are only one (where splitting direction would not vary with backazimuth), or from regions with a distinctly different layered structure.

The PI's have developed both a data analysis technique capable of making apparent splitting direction measurements from single SKS phases, and a modeling method capable of determining the layer parameters from the observations. Using data from a portable deployment they recently conducted on Kamchatka Peninsula, PIs Levin and Park also developed skills in measuring shear-wave splitting close to the surf line [Peyton et al., 2000].

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 - will be the primary tool to probe for the presence of sub-horizontal interfaces of the lithosphere. In the region of transition from oceanic to continental lithosphere we expect dramatic changes in lithospheric thickness, nature of the crust-mantle transition, layering and fabric within the subcrustal lithosphere.

In addition to the usual Radial-component receiver functions (which detect interfaces where P-SV conversion occurs), we will also employ Transverse-component functions (which detect interfaces with changes in anisotropy) (Levin & Park, 1997b, 1998a). These functions have proved extremely useful in constraining mantle fabric in other parts of the world (Levin & Park 1997a, 2000a).

PI's Park and Levin developed a greatly improved RF analysis algorithm based on spectral coherence estimates [Park and Levin, 2000a]. Experience of using this new tool on datasets from stable continental regions and convergent margins is very 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 carefull analysis of backazimuth-dependent receiver functions [Levin and Park, 2000a]. Similar analysis for a site on the western coast of the US yields evidence for a region of intense deformation located above the subducting Juan da Fuca plate [Yuan et al, submitted to JGR]. Of particular value is the ability of the algorithm to combine contributions from sources at virtually any distances. Figure 5 illustrates a continuous P-S converted phase from the Moho, clearly traceable across the entire epicentral distance range from 5 deg to 150 deg. The spectral coherence RF-estimation technique can analyze the high frequency energy in both core phases and regional seismic waves, offering improved resolution of shallow interfaces like the Moho, Hales and Lehmann discontinuities. Spectral averaging in the new technique, as discussed in detail by Park and Levin [2000a], limits the length of the "prediction filter" of Ps converted phases. For this reason the new method may not improve the retrieval of converted phases from the 420- and 670-km mantle discontinuities as dramatically as for shallow-converted phases. Ps phases from the deeper discontinuities have been imaged successfully in many locales, so we expect to detect them if they are there.

The location of the proposed array will allow us to construct epicentral-distance profiles like that shown in Figure 6 for the northwestern and southern directions on the basis of North- and Western Pacific and South American seismicity, respectively. Structure immediately below the central part of the array will be illuminated from two directions, making it possible to apply stacking techniques (e.g. Dueker and Sheehan, 1997; Kosarev et al, 1999).

Tomography Travel times of P and S body 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 and into the ocean. 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. The lithospheric North American shear-velocity model reported by van der Lee and Nolet (1997) has a striking anomaly in the region sampled by our array. We hope to improve the resolution of this anomaly, both laterally and in depth, to relate it to the findings of the other techniques (i.e. not tomographic) and to gain better understanding of its nature.

We have prior experience using teleseismic tomography imaging methods on smaller datasets from the New York and southern New England region, and are confident that the improved dataset can achieve a similar resolution across the entire proposed array. One of us (W. Menke) has recently finished a new tomographic imaging code, "raytrace3d" (available at ftp://lamont.ldeo.columbia.edu/pub/menke/raytrace3d.tar.Z)

that uses a three-dimensional tetrahedral representation of velocity.

Regional Wave Propagation Regional seismicity (e.g. within the western North Atlantic Basin, Mid Atlantic Ridge, Quebec and the Carribean (Figure 3), will be used to provide direct constraints on the elastic properties (velocity, anisotropy) of the lithosphere. Of particular interest will be variations in Pn and Sn phase velocities between the different regions, because they sample the very uppermost mantle that is poorly resolved by teleseismic tomography.

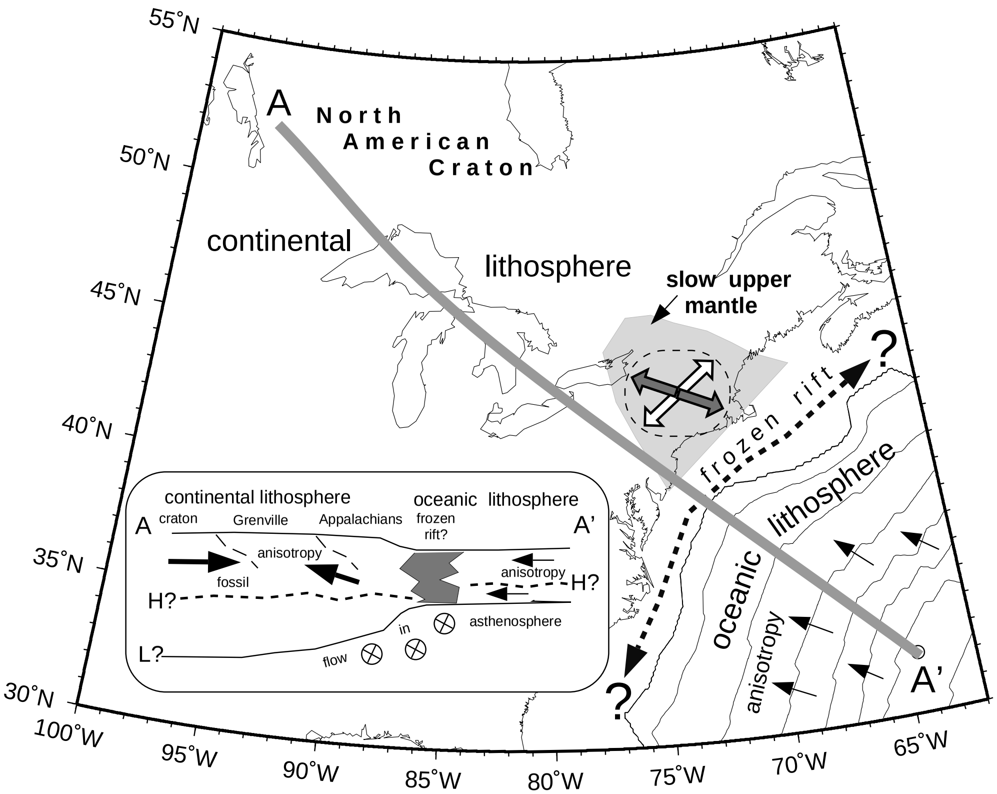
Management Plan All of the PI's will broadly participate in all phases of the project. Kim and Levin, both with significant experience in previous PASSCAL array efforts, will lead the land array deployment. Webb, who has long-term expeience with the manufacture and use of OBS's and Menke, who has used OBS's in a tomographic imaging experiment on the Juan de Fuca ridge, will head the OBS array deployment. Park has deployed PASSCAL hardware in Kamchatka, and will participate in deployment and maintenance operations, as will graduate students supported by this proposal. Once the data is collected, Park will head the surface wave related data analysis, Levin the receiver function and splitting analysis, Menke and Webb the body wave tomography, and Kim the regional wave analysis.

Use of Facilities The proposal requests use of three NSF-funded facilities: 1) We will request 10 broadband seismometers from the IRIS/PASSCAL pool for two years; 2) We will request the 16 long-deployment OBS's from the OBS pool for 15 months; and 3) We will request two cruises on an intermediate-class research vessel. Requests to use these facilities are have been filed with the relevant parties.

Timetable The main constraints on timing are on the deployment/recovery of the OBS's, which

are best done in May to September of the year, and the deployment of the PASSCAL instruments, which is best done when snow does not interfere with driving.
Year 1: Initial deployment of land array; Service and collect data from land array at 3 month intervals; Begin initial data processing of land data; Cruise to deploy OBS array.
Year 2: Continue to service and collect data from land array at 3 month intervals; Continue initial data processing of land data; Cruise to recover OBS array; Recover land array. Initial data processing of OBS data; Merge OBS and land data into synoptic dataset. Presenting initial results at scientific meeting.
Year 3: Final data processing; Interpretation of results; Writing up papers. Presenting initial results at scientific meeting.

Dissemination of Results We will submit both PASSCAL and OBS data to the IRIS DMC within two years of its collection, and to any other public archives that are required by the 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.



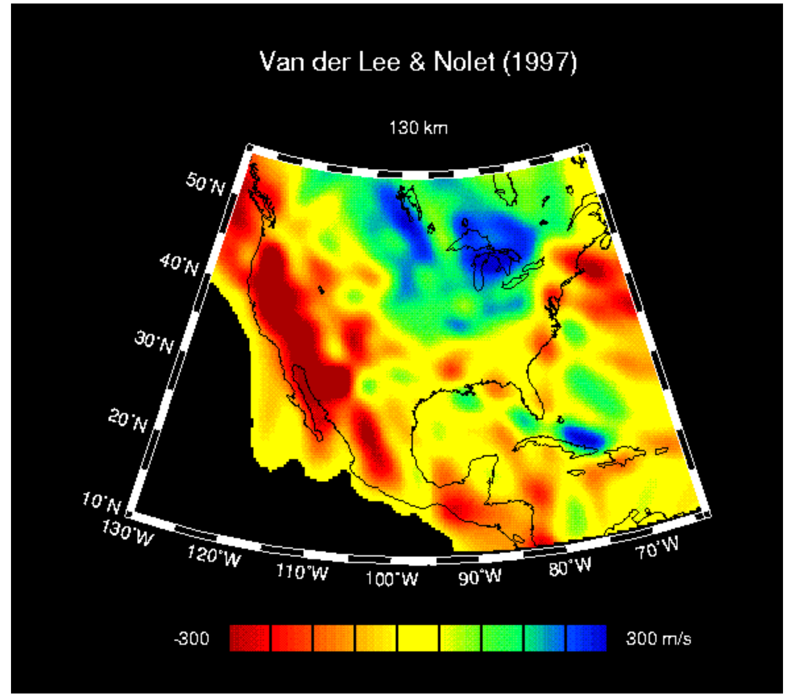


Figure 1. (left) Map of study region showing anomalous region of slow upper mantle (shaded), and directions of mantle strain inferred from seismic anisotropy (arrows). Two distinct anisotropic layers are shown for the continent (top, grey; bottom, white), one for the ocean (based on spreading direction). The schematic cross section AA' shows strain directions and hypothesized locations of Hales (H) and Lehmann (L) seismic discontinuities. (Right) Shear wave velocity at 130 km depth for North America (from van der Lee and Nolet, 1997) suggest that low velocity region may extend into the oceanic lithosphere.

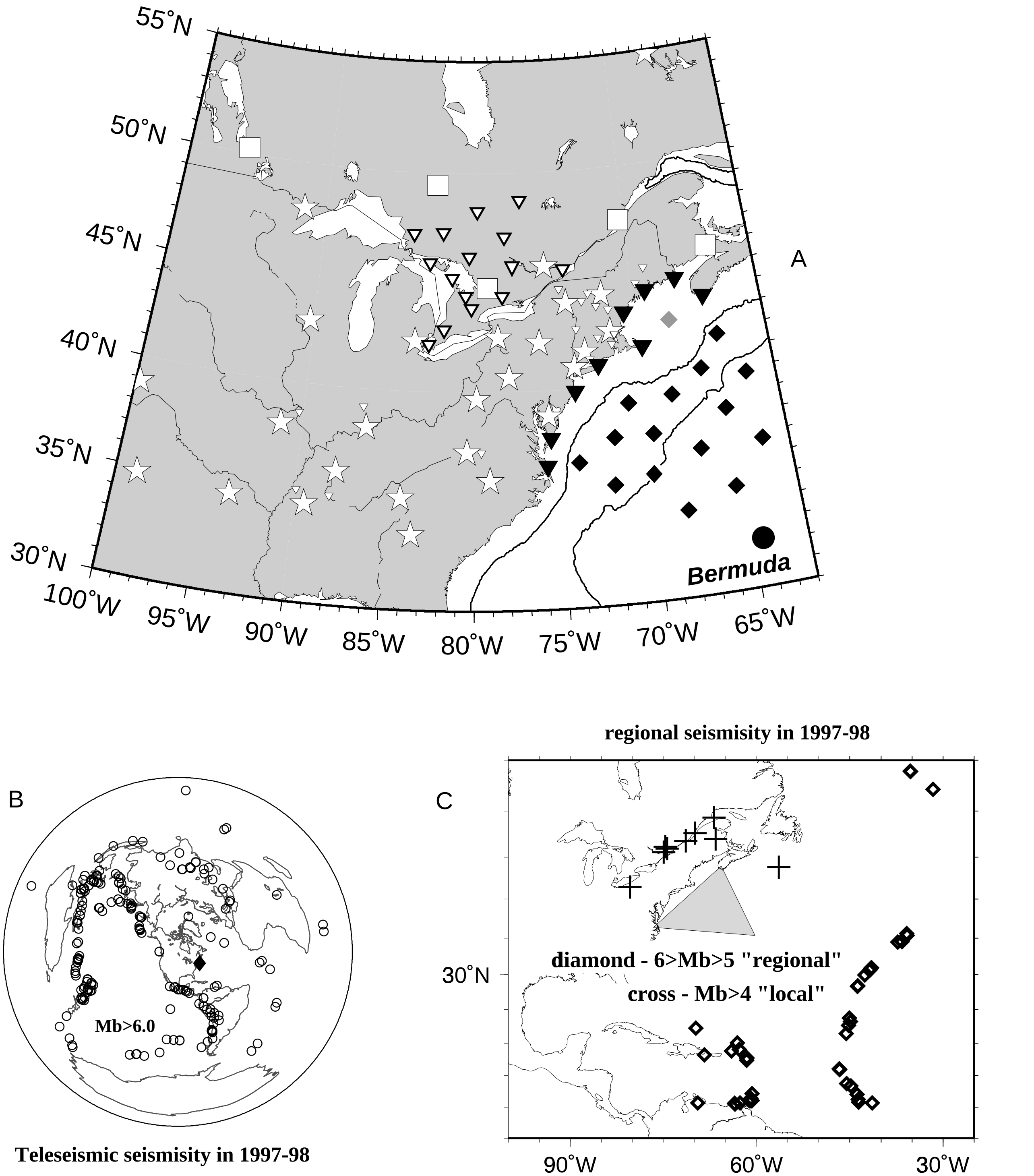


Figure 2. (top) Schematic map of the proposed array. White symbols show existing seismic installations (star - available through IRIS DMC, box - CNSN, triangle - regional networks, including Lamont Cooperative Seismic Network and some nodes of the POLARIS array in Canada). Filled diamonds indicate tentative locations of OBSs, filled triangles show tentative locations of PASSCAL portable observatories along the coast. (bottom left) Global seismicity with Mb>6.0 during a two-year period 91997-98. Study area is denoted by a filled diamond. (bottom right) Regional and local seismicity during a two-year period (1997-98). Outline of the proposed OBS deployment is shaded.

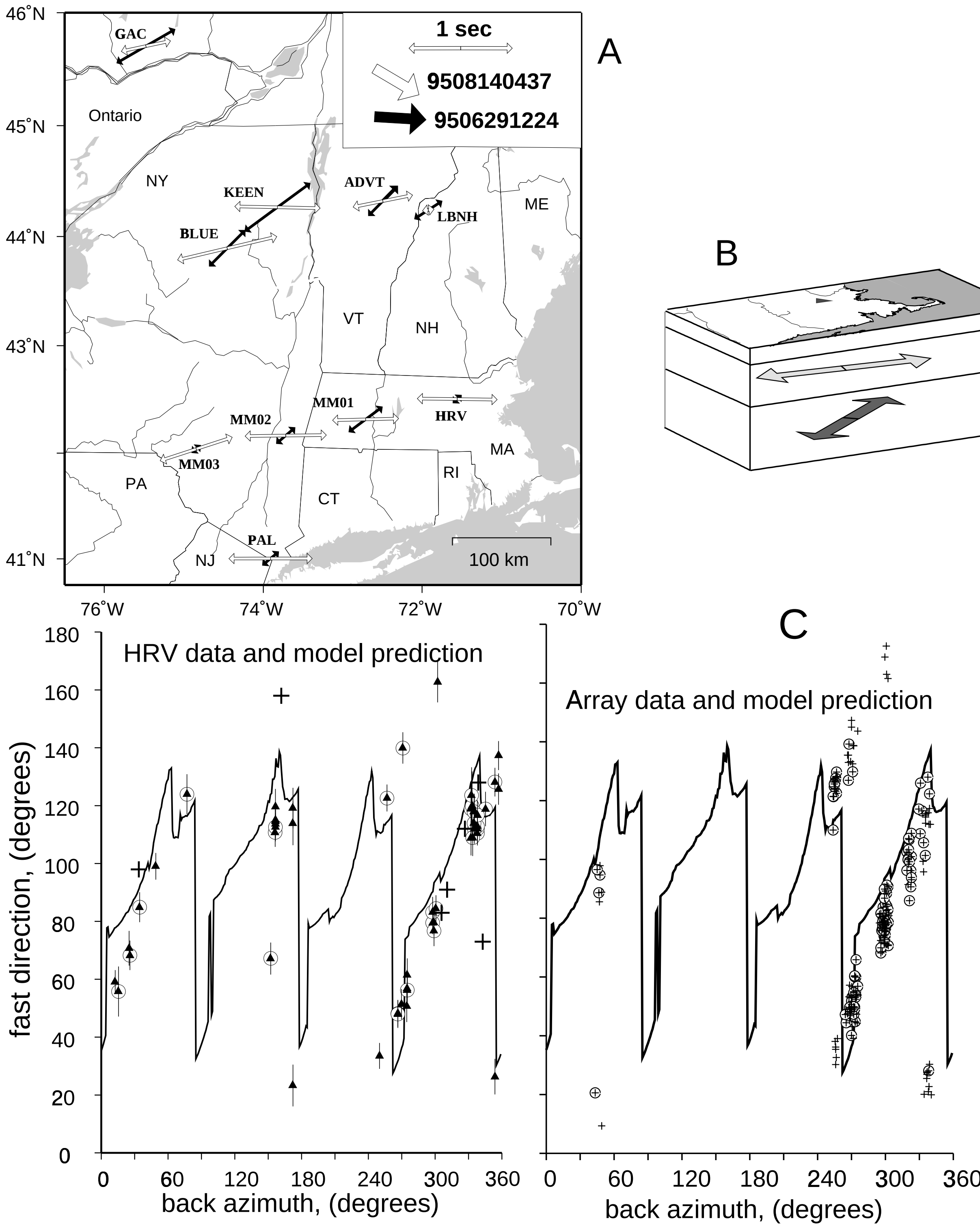
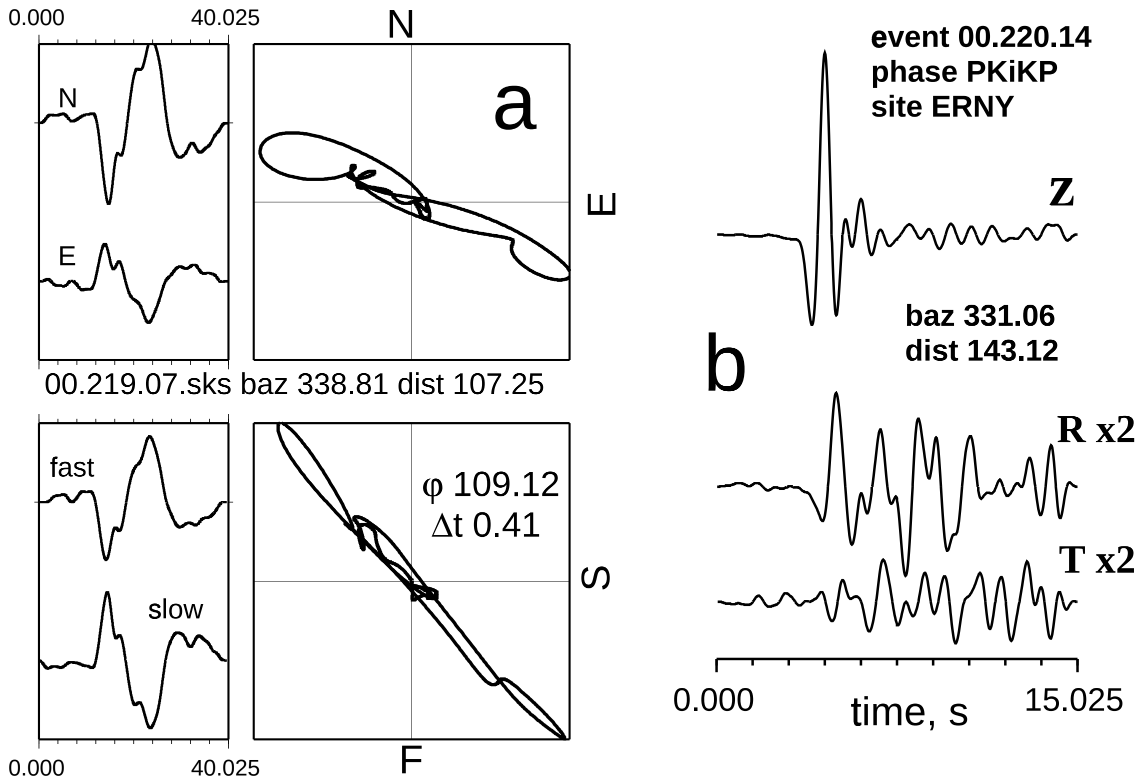


Figure 3. A) Map of the Northeastern US showing shear wave splitting parameters detemined for two core-refracted S phases. Splitting azimuth and delay are shown at each station as arrows aligned with fast direction and scaled with delay. Splitting arrows, as well as phase vectors in the upper right, are coded by event, solid arrows for one and open arrows for the other. Splitting direction for the two events is quite different, yet is fairly consistent across the region for each event. B) A schematic representation of the model for seismic anisotropy distribution under HRV (from Levin et al, 1999) C)Observed and predicted variation of the apparent fast direction. See Levin et al (1999, 2000b) for details. (Left) Data for station HRV, covering 1990-1997. Observations are shown by triangles (Right) Data for all stations shown in A) observed during the spring and summer of 1995. 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, shown in B, for one value of phase velocity.



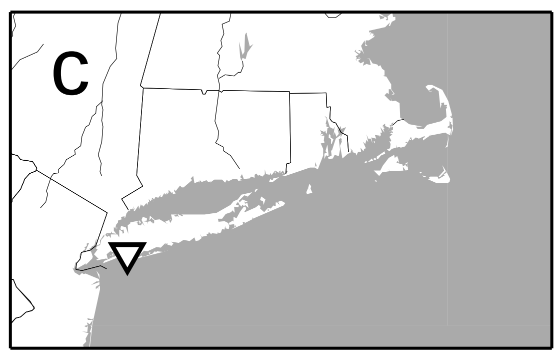


Figure 4. Sample observations from ERNY (East Rockaway, NY). Installation consisted of a REF TEK data logger and a CMG40T sensor placed on the surface in a small fiberglass enclosure.
a) Shear wave splitting measurement on an SKS phase. Waveforms are filtered in 0.025-0.3 Hz passband. Upper panels show observed data, lowerpanels show waveforms corrected for the effect of anisotropy. Splitting parameters are shown in the lower right panel: fast direction φ = 109.12°, delay is 0.41 s. Note reduced ellipticity of particle motion. This observation aggrees well with measurements further inland (Levin et al, 2000), suggesting continuity of structures. **b)** PKiKP phase from an earthquake 143° away is particularly bright due to a caustic in the travel time curve. Waveforms are filtered in 0.025-1.5Hz passband. Motion on horizontal components is a result of near-surface reverberations that form data for receiver function analysis. Of particular interest is SH-polarized motion (T component) indicative of lateral heterogeneity and/or anisotropy.
c)Location of the station on the oceanward shore of Long Island.

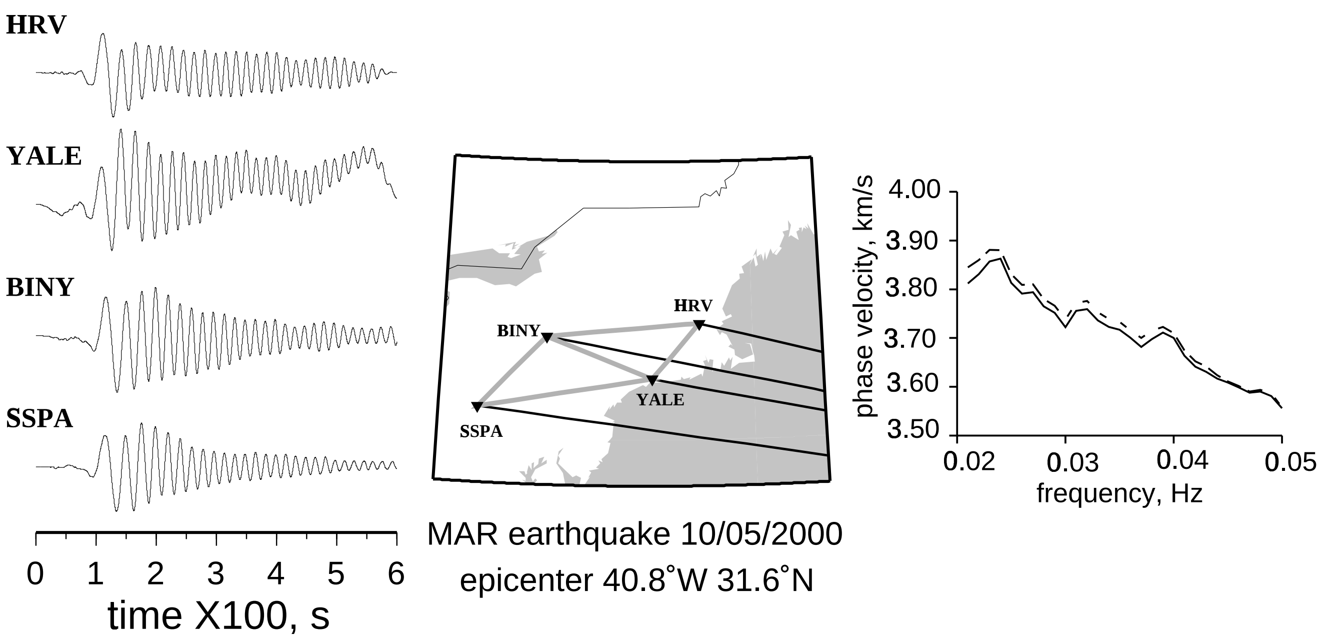


Figure 5. (left) Well-dispersed Raleigh wave from a Mid-Atlantic Ridge earthquake observed on four vertical-component broadband stations in Northeastern US. (middle) Map showing four stations (HRV, YALE, BING, SSPA), which define southern and northern trianges. (right) Local estimate if phase velocity for each triangle, computed with the differential phase method. Note that the northern triangle (solid curve) has systematically lower velocities.

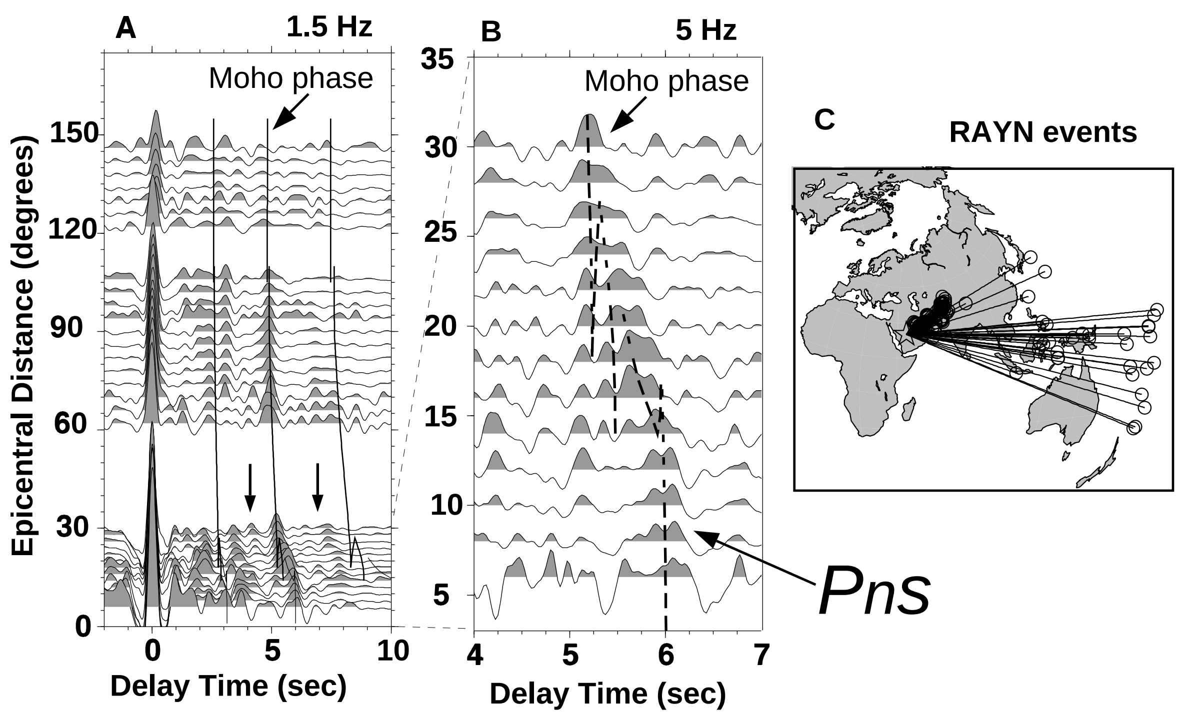


Figure 6. A) Radial receiver functions (RF) computed for GSN station RAYN (Ar-Rayn, Saudi Arabia), averaged in epicentral-distance bins with 50% overlap (10° bins for 60°<Δ < 160°; 2° bins for 5°<Δ <30°). Results for broadband data (channel BH, 20 sps) are shownfor eastern backazimuths, with RF spectra limited at 1.5Hz. Superimposed delay curves are computed for the three P-S converted phases that would arise from interfaces at 21, 41 and 72 km depth in a simple velocity structure based on the model for RAYN suggested by Levin & Park (2000a). The phase velocities of incoming *P* and *Pn* waves are computed for a source at 15 km depth using the IASPEI91 model and software. The hypothetical Moho head-wave conversion *Pn*s has a near-constant delay of ~6 s for 0°<Δ < 17°. Arrows show time interval expanded in panel B. B) Regional and near-teleseismic RAYN receiver functions, averaged in 2° epicentral-distance bins. Results for broadband data (channel HH, 40 sps) are shown for eastern backazimuths, with RF spectra limited at 5Hz. Dashed lines show delay curves for converted phases, as in A. C). Map of sources used in RF analysis.