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/

Goal. Compare seismic anisotropy, a proxy for upper mantle strain−induced fabric, across the conjugate margins of northeastern North America and northwestern Africa, in order to test the hypothesis that the lithospheric fabric in northeastern North America is a fossil remnant of Paleozoic delamination and that asthenospheric fabric is related to present−date plate motions.

Introduction. Studies of seismic anisotropy, such as are commonly conducted with SKS waves, have enabled geophysicists to begin to map out the strain−induced fabrics of the upper mantle and to attempt to understand the deformation fields that cause them. However, one impediment towards this agenda is the ambiguity between fabrics that are fossil (e.g. caused by ancient orogenic events) and fabrics that are maintained by present−day deformation (e.g. asthenospheric convection). Northeastern North America is one well−studied area in which two mantle fabrics are demonstrably present at different depths in the upper mantle, with one fabric being ascribed to fossil strain of the lithosphere during an Appalachian delamination event, and the other being ascribed to present−day asthenospheric shear. We propose to study the anisotropic fabric on the northwestern African margin at Morocco, which is conjugate to northeastern North America. The Paleozoic continuity of the now−distinct plates gives us a way of testing the fossil−delamination interpretation of the lithosphere. The different absolute plate velocities of the two continents gives us a way of testing the asthenospheric shear interpretation of the lower layer. Finally, present−day lithosperic delamination is thought to be occuring just north of northernmost Morocco. Studies of its associated fabric will provide a point of comparison for the supposed fossil signal in northeastern North America and, more generally, information about the strain field against which geodynamical models of delamination can be tested.

Convergence of two continental plates can not be accommodated by the complete subduction of one of them under the other, due to their buoyancy. Instead, a scenario in which the dense mantle lithosphere thickens, delaminates, and eventually detaches and sinks into the mantle, is likely (e.g., Houseman et al, 1981). The exact process of such lithospheric mantle delamination depends on many parameters, including the initial thickness, density and vertical strength profiles of the two plates (Conrad and Molnar, 1997; Meissner and Mooney, 1998; Schott and Smelling, 1998), as well as the rate and the time history of the convergence (e.g., Pysklywec et al, 2000). The end results, however, are similar: Crustal uplift, extension and thinning occur as warmer asthenospheric material rises to replace the colder lithospheric mantle. Extra heat leads to volcanism, with geochemical signatures indicative of continental lithospheric material being the source of melts. Upon thermal equilibration, subsidence occurs in the delaminated area.

In addition to geochemical signatures, crustal thickness changes and the uplift−subsidence sequence, the process of lithospheric delamination is likely to leave its "signature" in the fabric of the mantle (and/or crust) that remains. A narrow depth interval of highly concentrated strain directed towards the center of the detachment is predicted in most numerical simulations of the detachment/delamination process (e.g., Schott and Smelling, 1998; Pysklywec et al, 2000; see Figure 1 for examples). If other tectonic processes do not affect the region, the rock fabric associated with this strain is likely to remain "frozen" within the body of the continent. Such fossil strain−induced fabric should be detectable in the form of seismic anisotropy, caused by lattice−preferred orientation (LPO) of olivine (Zhang and Karato, 1995), whose mineral fast axes tend to align with the axis of maximum extension (Ribe, 1992).

Recently, evidence has been presented (Levin et al, 1999, 2000b) that the upper mantle beneath a large area of Northeastern North America does indeed contain a layer of frozen rock fabric with orientation that is best explained as resulting from the delamination event at the close of the Appalachian Orogeny (see following section for details). Given the large aerial extent of the inferred fabric, this event must have taken place over a broad area which is likely to have included present−day northwestern Africa (e.g. Morocco) (Figure 2). We therefore hypothesize that the sub−crustal mantle under Morocco contains the signature of the strain associated with this episode.

During the opening of the Atlantic, Africa experienced little net rotation relative to North America (e.g., Le Pichon et al, 1977). We can therefore predict that the fossil strain of the "Appalachian" delamination event will have similar orientation to that observed in Northeastern North America (N115E). Furthermore, other geographically localized episodes of lithospheric delamination appear to be occurring today beneath Morocco (Ramdani, 1998) and north of it, under the Alboran Sea (e.g., Seber et al., 1996) (Figure 3D). In case of the later, the pattern of intermediate depth seismicity indicates that a compact object is sinking into the asthenosphere. We can therefore predict that the strain field associated with this episode will have radial symmetry, with the sub−crustal mantle under northern Morocco having a fabric oriented in north−south direction. We therefore hypothesize that the lithospheric LPO should rotate from an nearly east−west "Appalachian" signature in southern Morocco to a more north−south "Alboran" signature in the north, with likely complications from the processes under the Middle Atlas mountains. The length scale over which such rotation occurs provides an important constraint on the geodynamics of the northern Morocco − Alboran region, as well as on the process of lithospheric delamination.

LPO in Northeastern North America. Initial shear−wave splitting observations from the northeastern North America have been attributed to the fabric that represents the fossil strain acquired during the Appalachian orogenies (e.g., Barruol et al. 1997). An alternative explanation, in terms of fabric reflecting present−day strain associated with absolute plate motion, was explored by Fouch et al. (2000). We have recently presented data that we interpret as indicating that *both* of the explanations are correct, as the mantle in this region has two distinct layers of mantle fabric each of which is caused by one of these processes. When "split" shear waves from a large set of teleseismic earthquakes are analyzed, the apparent fast axes of individual shear waves are found to vary strongly with their arrival back−azimuth (Figure 4A). This pattern is diagnostic of two layers of rock, whose different anisotropic directions "interfere" with one another (Levin et al. 1999). A more−or−less uniform pattern is observed across northeastern North America, indicating that these two layers are quite widespread. Even very coastal locations (e.g. southern Long Island, New York) have the pattern (Figure 4B).

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 crust−mantle Moho discontinuity at station HRV (in Massachusetts) precludes the top layer of anisotropy from residing in the crust (Levin et al. 1999). When the anisotropic mantle is modeled as 6% anisotropic (typical of strained mantle), the upper and lower layers are 60 and 90 km thick, respectively.

This anisotropy model bears an important relationship to the structure and dynamics of the lithosphere in this region. The inferred fast−axis directions are horizontal in both layers. In the lower layer the fast axis azimuth (S53W) is sub−parallel to the absolute plate motion of North America (S65W) as reported by Gripp and Gordon (1990). In the upper layer the fast axis is nearly perpendicular to the local trend of the Appalachian orogen.

The lower layer is interpreted to lie within an actively deforming asthenosphere, with anisotropic rock fabric maintained by contemporary plate motion. The upper layer is interpreted to reside in the stable part of the continental lithosphere, with a frozen fabric that formed during a past deformation event. The near−uniform anisotropic properties beneath the northeastern North America contrast with regional variations of geology within the Appalachian orogenic belt, as well as with significant short−scale variations in isotropic shear velocity (Levin et al 2000b). 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 Appalachian terranes to the Proterozoic Grenville province. The upper layer of anisotropy beneath the northeastern North America is therefore likely to be associated with convergent "Appalachian" tectonism in the late Paleozoic. The orientation of the two fabrics is shown in Figure 3C.

Several other lines of evidence suggest that a mantle strain event, consistent with both the idea of delamination and the observed LPO direction, accompanied the Appalachian orogeny (which began around 390−−410 Ma, depending on the reconstruction, and ended with the cessation of thrusting, magmatism and thermal metamorphic activity at about 275 Ma). This evidence includes removal of 15 km or more of upper crust by erosion (Carmichael, 1978), which implies high topography during the late Paleozoic; granitic magmatism and thermal metamorphism, indicating high heat flow (Zartman, 1988; Lux and Guidotti, 1985; Sevigny and Hanson, 1993); and crustal extension (Getty and Gromet, 1992). Mantle−derived magmatism and mafic underplating have been observed or inferred for various late Paleozoic New England igneous rocks (Hannula et al. 1998; Wiebe et al. 1997).

Appalachian−age and Present−Day Delamination in Morocco. In Morocco, the geochemistry of some instrusive rocks formed during the post−collisional Hercynian (late Devonian) orogeny indicates partial melting of the continental lithospheric mantle (e.g., Ajaji et al., 1998), while others carry an asthenospheric signature (Gasquet et al, 1992). Also, studies of Variscan−age subaerial extrusive rocks imply continuous uplift and extensive tensional fracturing of the crust (Chalot−Prat, 1995). Ajaji et al. (1998) argue that, in concert, these observations favor a geodynamic scenario where lower lithosphere is replaced by the hot asthenospheric material, i.e. a delamination event. On the basis of their proximity in time and spatially (in Pangean reference), we speculate that this is the same episode of unrooting that has left its mark on the conjugate North American margin in the form of anisotropy−inducing frozen fabric.

The concept of lithospheric delamination dominates the literature on the present−day geodynamics of Morocco. Seber et al. (1996) summarize the evidence pointing to an episode of geologically recent lithospheric delamination under the Alboran Sea. This evidence includes seismicity extending to depths in excess of 600 km (without a clearly defined subduction zone), reduced seismic velocity and high attenuation in the mantle, and velocity structure implying recently extended continental crust under the Alboran Sea (Figure 3D). Zeck (1996) present a review of exhumation and cooling data that constrain the timing of the delamination episode to "shortly before 22 Ma". This scenario is a subject of continuing debate, however, with alternative scenarios including a short−lived episode of subduction (Ramdani, 1998). A detailed seismic tomography image constructed by Calvert et al. (2000) shows a nearly−continuous streak of elevated seismic velocities from lithospheric depths to 600 km under the Alboran Sea. The geometry of this image is largely consistent with predicted behavior of gravitationally unstable lithosphere during continental convergence (e.g., Pysklywec et al., 2000). A spectrum of unrooting scenarios described by Pysklywec et al., (2000), from subduction−like mantle lithosphere peel−off to a dripping Rayleigh−Taylor instability, is controlled by convergence rate and choices on rheology and density profiles. Notably, most simulations show intense sub−horizontal shearing of upper mantle material, and would predict intense anisotropy−inducing fabric. In the Central Atlas region of Morocco, geochemical and geoelectric data, rapid uplift, reduced seismic velocities in lower crust and presence of unusual intermediate−depth earthquakes lead Ramdani (1998) to propose that the region has been unrooted by another delamination episode, synchronous to or post−dating the unrooting in the Alboran Sea region.

Hypotheses that will be Tested

1. The mantle lithospheric LPO identified in northeastern North America is the fossil signature of the Appalachian orogeny, and as such extends into the African side of the orogen. Consequently, the lithosphere there should have an LPO direction similar to the N115E direction observed in in northeastern North America.

2. Present−day Alboran delamination is occurring and is associated with north−south mantle strain in northern Morocco. Mantle lithospheric LPO directions should therefore rotate from nearly east−west in southern Morocco to roughly north−south in northern Morocco.

3. Asthenospheric LPO is caused by shear between the lithospheric plates and the asthenosphere, and is parallel to the direction of absolute plate motion. Whereas North America is moving in hotspot frame, northwest Africa is almost stationary. Thus we expect asthenospheric LPO to be weaker in northwest Africa than in northeastern North America.

Benefits and Possible Pitfalls. As we will show from two preliminary studies, there is every reason to believe that the mantle beneath Morocco has significant anisotropy. We thus have every confidence that the project will be able to map out this anisotropy, in both its geographical and depth extents. On the other hand, our hypotheses are built around the assumption that there is in fact a relationship between this mantle fabric and known, large−scale past and present−day geodynamical processes (delamination, absolute plate motion). Our data may show this to be the case, or it may not. If it does show it to be consistent, our confidence in the theory of delamination, and in the existence of shear caused by large−scale plate motions, would be very significantly strengthened. On the other hand, it could be consistent with only one of the hypothesized patterns. The data that we collect would, for instance, be able to determine, say, that the lithosphere has an Appalachian fabric but the asthenosphere has a much stronger fabric than can be accounted for by the sluggish absolute plate motion. Such a result would suggest that an effort to map out more regional−scale asthenospheric flow might be warranted. Finally, the results may be consistent with none of the hypothesized patterns. Such an outcome might at first seem disappointing. But in our opinion, such a result would in fact be quite valuable, since it would indicate that more "minor" geodynamical events were capable of "resetting" the fabric of the mantle.

Some preliminary measurements of Anisotropy in northwest Africa. Seismic station MDT (part of the Internation Monitoring Network) (Figure 3A) has been in operation episodically since 1989. Continuity of operation improved notably in the last few years. A set of records containing SKS phases have been retrieved from the IRIS DMC. Parameters of shear wave splitting are shown in Figure 4C. A clear evolution of apparent fast direction with backazimuth is observed. Also, intensity of splitting (the amount of delay between fast and slow share waves) varies considerably with direction, reaching almost 2 s. While the pattern of fast direction change with backazimuth is obviously different from that seen on the other side of the Atlantic (Figure 4A), it has a similar slope, possibly suggesting a similar mechanism (i.e. multilayered anisotropy at depth). Lateral variation in anisotropic signature can not be ruled out on the basis of this limited data set, though. A recent study of Pn compressional velocities (sensitive to the velocity structure just below the crust−mantle transition) in northern Morocco finds about +/− 6 percent velocity variability (F. Ramdani, personal communication, 2001; Figure 4D). Some systematic variation with azimuth is observed, but the pattern is more complex that can be modeled by a single anisotropic layer.

The preliminary data, taken alone, are an insufficient basis for developing a model of LPO in northwestern Africa or for testing the above hypotheses. They do, however, provide strong evidence that significant mantle LPO is present there and that it is not of the simplest one−layer type. The MDT data show a strong variation of fast direction with azimuth, a trend that is consistent with multi−layered anisotropy. However, the Pn data may indicate that the uppermost layer has significant lateral heterogeneities. Both patterns are broadly consistent with the LPO patterns hypothesized to be present in the lithosphere of northwestern Africa, but more data is needed to make a definitive determination.

Proposed Research. In order to address the hypotheses described above we need to have measurements of mantle anisotropy over a broad swath across Morocco that spans both the northern Alboran region in which present−day delamination may be occurring, and to the central and southern parts which we believe are most analogous to northeastern North America. The four broadband stations currently operating in this region (two in southern Iberia and two in northwestern Africa, Figure 3A) will provide some useful data, but are themselves insufficient to address these questions. They can address the hypothesis related to the fabric associated with the Alboran delamination, but are too far north and two far from the Atlantic to determine whether an Appalachian−like fabric is present.

We therefore propose the deployment of a passive array of broadband seismic stations in Morocco that supplements the permanent stations. This array would be closer to the Atlantic coast, and would extend further to the south, than the existing stations. While it is tempting to imagine an extremely dense deployment of numerous stations, our experience from northeastern North America (and elsewhere) is that a coarse network, with station spacing of a few hundred kilometers, will be sufficient to address all the goals of the study. We therefore propose to supplement the existing stations with six (6) temporary broadband stations (Figure 3A). Morroco is well positioned with respect to teleseismic sources, and especially for observation of splitting that utilize core phases (Figure 3b), so a reasonably short period of operation of 18 months will be sufficient. Data from regional earthquakes, and especially the intermediate−depth Alboran seismicity (filled circles in Figure 4D) will also be very useful, because it will provide control of the depth of the anisotropy. Data from these temporary stations will be supplemented with data from the four permanent broadband stations, and (to the extent possible) with short period data from Morocco’s permanent earthquake−monitoring array.

Collaboration with Mohamed V University, Rabat. This proposed research will be conducted in collaboration with the Department of Physics of the Earth of Mohamed V University (Rabat, Morocco) (see Letter of Collaboration in supplemental documents section). Three scientists from that University will actively participate: Mimoun Harnafi (Head of the Department, who studies signal processing), Faiçal Ramdani (seismolgist, currently studying anisotropy), and Fida Medina (geologist, interested in seismotectonics). In order to reduce operating costs, the broadband stations will be co−located with existing short−period stations in Morocco. The tentative proposed schedule is to deploy the instruments in the fall, and to remove them in the spring, 18 months later.

Main Data Analysis Techniques

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 4A). This directional dependence is key to detecting layers with distinct anisotropic properties. Fortunately, the expected distribution of teleseismic sources mainly from the circum−Pacific subduction zones, relative to Morocco are very favorable for this purpose.

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.

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). These functions have proved extremely useful in constraining the depth of mantle LPO in other parts of the world (Levin & Park 1997, 2000a).

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. Figure 6 illustrate 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.

Ancillary Data Analysis Techniques. While the main emphasis of this proposal is on mantle LPO fabric and its relationship to the geodynamic process of delamination, the array will of course collect data that are relevant to several other important issues that can be addressed with other methods:

Teleseismic S−wave Tomography Travel times of S body waves will be used in first−order tomographic imaging, in order to better image the Alboran delamination event and to map out other major features in the mantle. We have prior experience using teleseismic tomography imaging methods on smaller data sets from the New York and southern New England region, and are confident that we can achieve a resolution of about 150 km resolution across all of Morocco. One of us (W. Menke) has recently finished a new tomographic imaging code

ftp://lamont.ldeo.columbia.edu/pub/menke/raytrace3d.tar.Z

that uses a three−dimensional tetrahedral representation of velocity.

Rayleigh wave dispersion Estimates of shear wave velocity variation with depth can be obtained using observations of phase velocity of fundamental−mode surface waves. While a variety of techniques are available for estimating phase velocity dispersion curves from broadband data, we have been particularly interested in the "three−station" technique. With this technique, differential phase measurents are made on a triangular sub−array of three broadband stations, and used to infer a "local" estimate of phase velocity (Figure 5). Both variations in phase velocity with azimuth, due to anisotropy and dipping interfaces, and between sub−arrays, due to lateral heterogeneity, can be investigated. Several authors, including van der Lee and Nolet (1997), Aibing Li (personal communication, 2001) and ourselves (Menke and Levin, 2001, submitted, www.ldeo.columbia.edu/users/menke/NETRI/) have performed studies of Rayleigh wave dispersion in northeastern North America, to which the northwest African measurements can be compared.

Full−waveform moment−tensor inversions. Little is known about the state of stress in the mantle within and near the Alboran delamination event, largely because of the difficulty of constructing traditional first−motion focal mechanisms for the smallish, deeper earthquakes. The broadband data will allow the application of modern waveform−fitting techniques (e.g. Kim, 1987) that require fewer stations to achieve a reliable mechanisms and hypocentral depths.

Management Plan

William Menke will be responsible for the overall management and timely completion of the project. All members of the collaboration (William Menke, Vadim Levin, Mimoun Harnafi, Faiçal Ramdani and Fida Medina) will participate in all phases of the project. A meeting of all collaborators will be held at at LDEO at the start of the project to develop a detailed logistical plan for the field deployment, to share expertise and to provide training with equipment and software. Menke and Levin, both with significant experience in previous PASSCAL array efforts, and Faiçal Ramdani, who is a leading expert in the seismology of Morocco, will lead the field deployment. Mimoun Harnafi, who is head of the Department of Geophysics and an expert in signal processing, together will Faiçal Ramdani, will supervise the operation of the array. Once the data is collected, Vadim Levin will lead the data analysis and William Menke and Faiçal Ramdani, assisted by a graduate student, will lead the modeling effort. F. Medina and W. Menke will interpret the focal mechanism data. All collaborators will participate in the final interpretation of the results.

Use of Facilities

The proposal requests use of NSF−funded facilities: We have requested 6 broadband seismometers from the IRIS/PASSCAL pool for 18 month.

Timetable

The main constraints on timing are scheduling the use of the IRIS/PASSCAL seismometers.

Year 1:

July: Begin collecting data from permanent (non IRIS/PASSCAL) stations.
July: Meeting of Collaborators at LDEO.
September: Deployment of seismic array.
January: Service seismic array, download data.
Spring: Begin processing and interpreting data.
May: Service seismic array, download data.

Year 2:

September: Service seismic array, download data.
January: Service seismic array, download data.
May: Service seismic array, download data.
May: Meeting of Collaborators at LDEO.
June: Begin final assembly and interpretation of results.

Dissemination of Results

We will submit IRIS/PASSCAL data to the IRIS DMC within two years of its collection. 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/research_results.html
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.

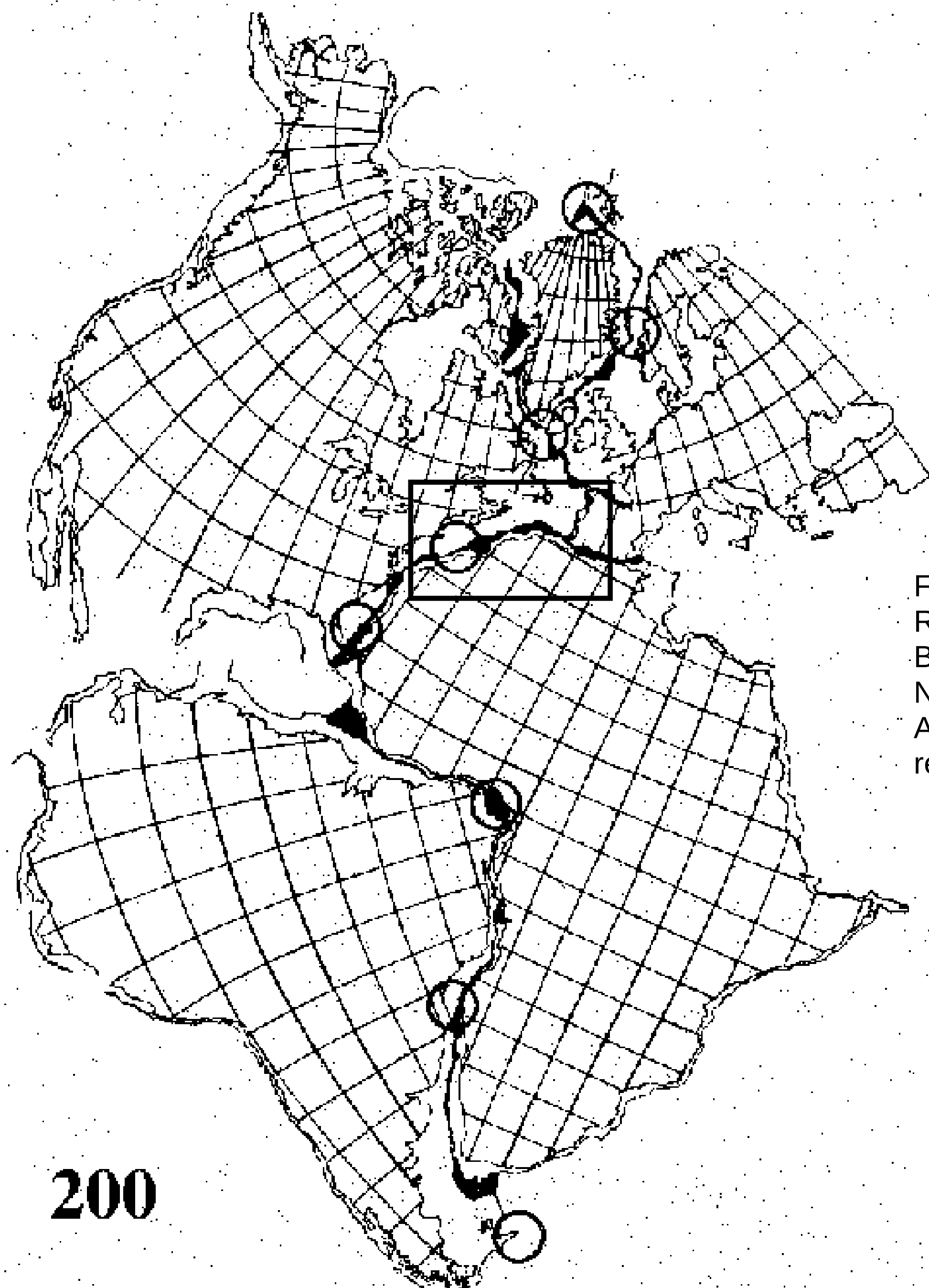

Figure 2. Plate Tectonic Reconstruction at 200 Ma. Box, spanning northeastern North America and northwestern Africa (incl Morocco) indicates region of interest.

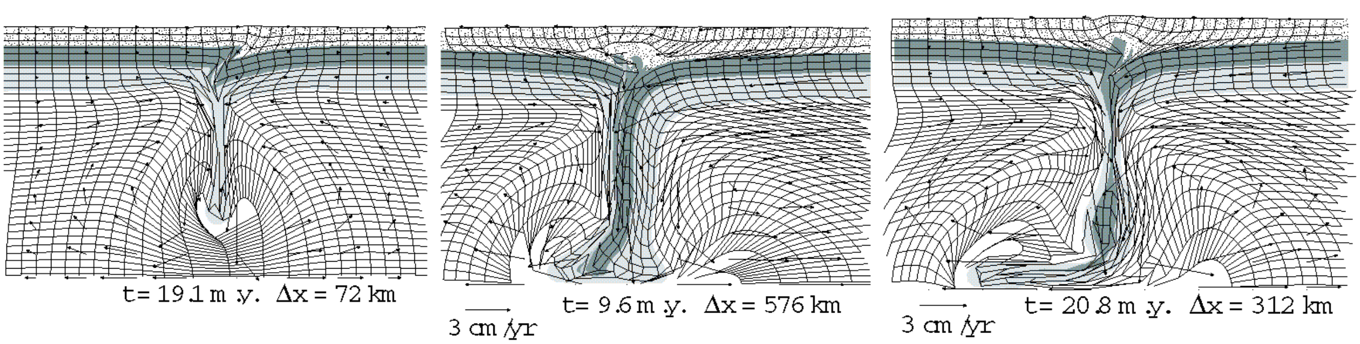

Figure 1. Styles of lithospheric deformation during tectonic convergence (adapted, with permission, from Pysklywec et al., 2000). (left) convergence-induced lithospheric thickenning results in a dripping Rayleigh-Taylor-type instability after convergence stops; (middle) a subduction-like behavior dominates if the rate of convergence is high; (right) in an intermediate case, lithosphere subducted to a certain depth in the mantle detaches and sinks. Material of the uppermost mantle (below the shaded lithosphere) experiences extensive subhorizontal deformation.

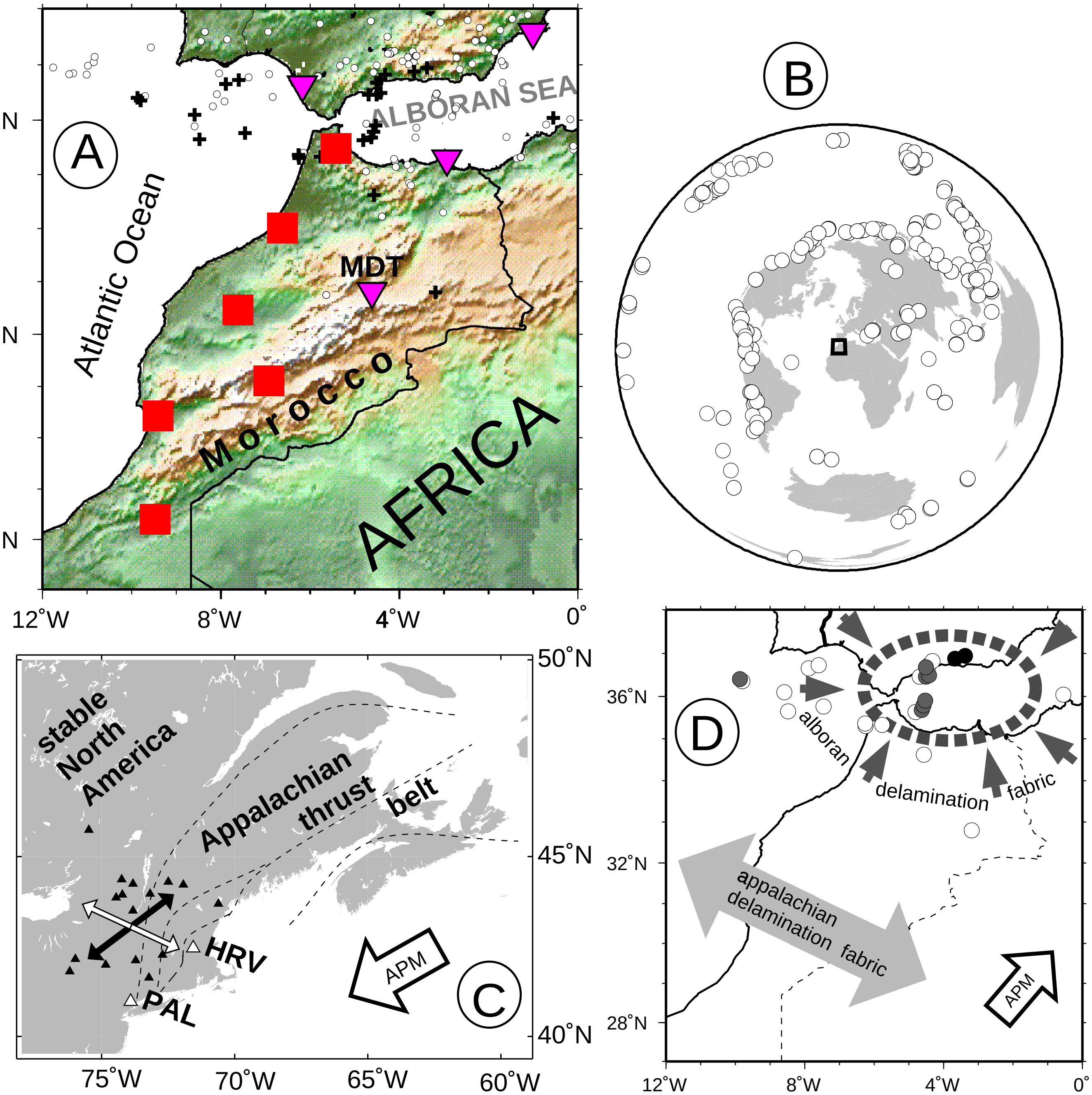

Figure 3. *A)* The area of the proposed study. Permanent seismic stations are shown with inverted triangles. Locations of temporary sites were chosen to coincide with existing installations of the seismic network operated by Institute Scientifique (Rabat). Regional seismicity (M>3.8) in a two-year period (1998-99) is shown by small circles. Crosses show 10 years (1990-99) of deep (below 50 km) seismicity. *B*) Global seismicity (M>6) during an 18-month period (10/01/1998 - 05/01/2000). The study area is shown by the box. *C)* Anisotropic fabric of the northeastern Appalachians (see Levin et al., 1999). Open arrow shows plate motion direction in "no net rotation" reference frame. *D)* Expected orientations of anisotropy-inducing fabric in the upper mantle of Morocco. Frozen fabric from the delamination episode during the Appalachian orogeny (grey arrow) should be present throughout the region. It is likely to be disrupted by more recent tectonic activity in the northern part of Morocco, especially the Alboran Sea delamination episode (e.g., Seber et al., 1996). Open arrow shows plate motion direction in "no net rotation" reference frame.

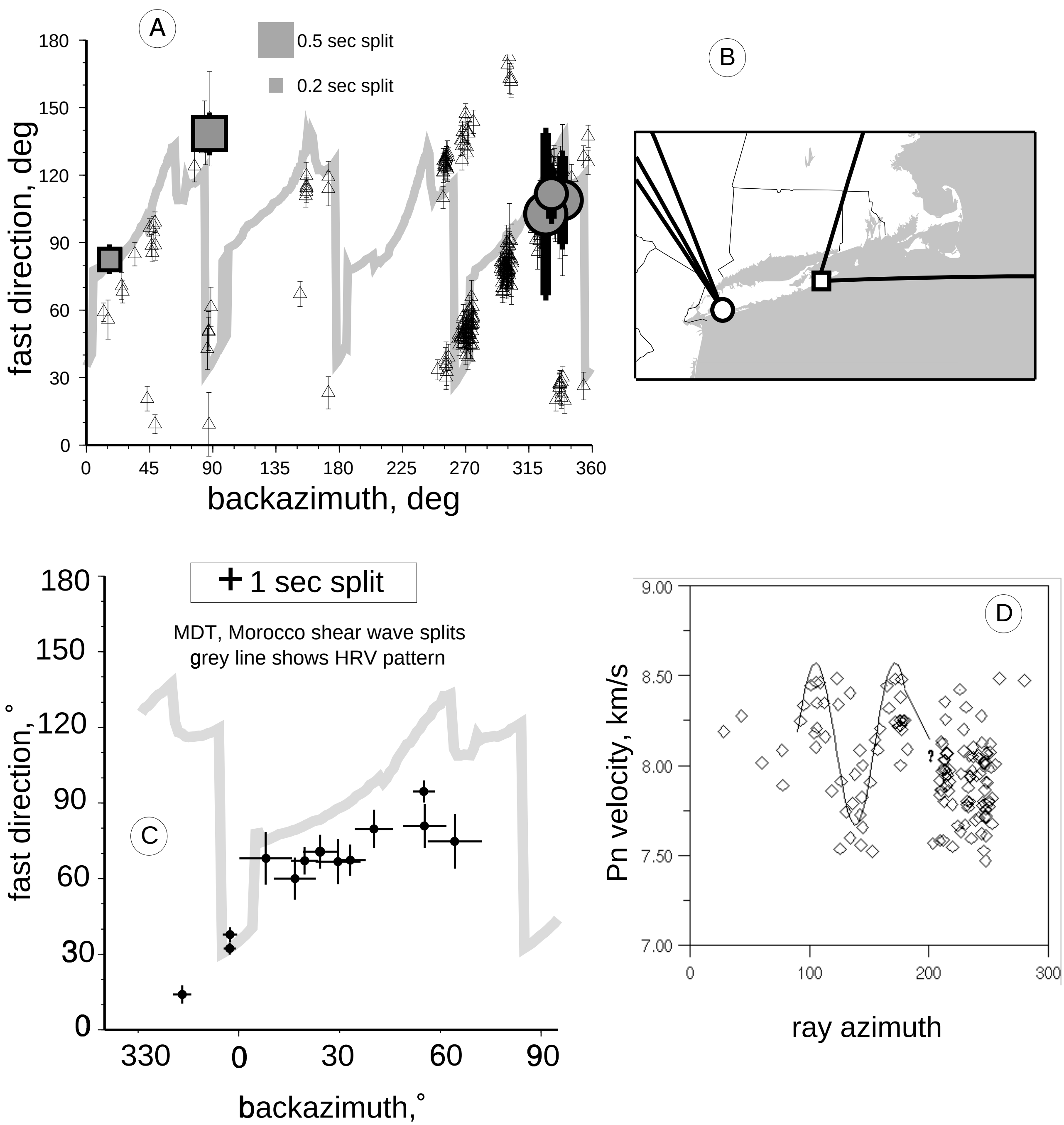

Figure 4. Observations of seismic anisotropy in Northeastern North America (NNA) and Northwestern Africa (NWA). (A) Azimuthal dependence of observed and predicted fast shear wave speed orientation in NNA. Triangles with error bars show a compilation shaer-wave birefringence measurements from stations in the region (station locations shown in Figure 3A, observations discussed in Levin et al. 1999; 2000). Grey line shows a pattern of fast directions predicted by a 2-layer model for station HRV. Large symbols (squares and circles, size proportional to amount of splitting) show recently obtained observations on Long Island. Station locations (corresponding symbols) and SKS ray directions are shown on in (B). (C) Directions (squares) and values (cross sizes) of shear-wave birefringence observed at seismic station MDT in NWA (see Figure 3A), as a function of ray backazimuth. Grey line shows a pattern of fast directions predicted by a 2-layer model for station HRV in NNA. While the patterns clearly differ, a general similarity of slopes suggests that variation at MDT is likely to reflect verticaly stratified anisotropy. (D). Azimuthal variation of Pn velocity in northern Morocco (F. Ramdani, personal communication) presents a complicated pattern suggestive of lateral differences in properties.

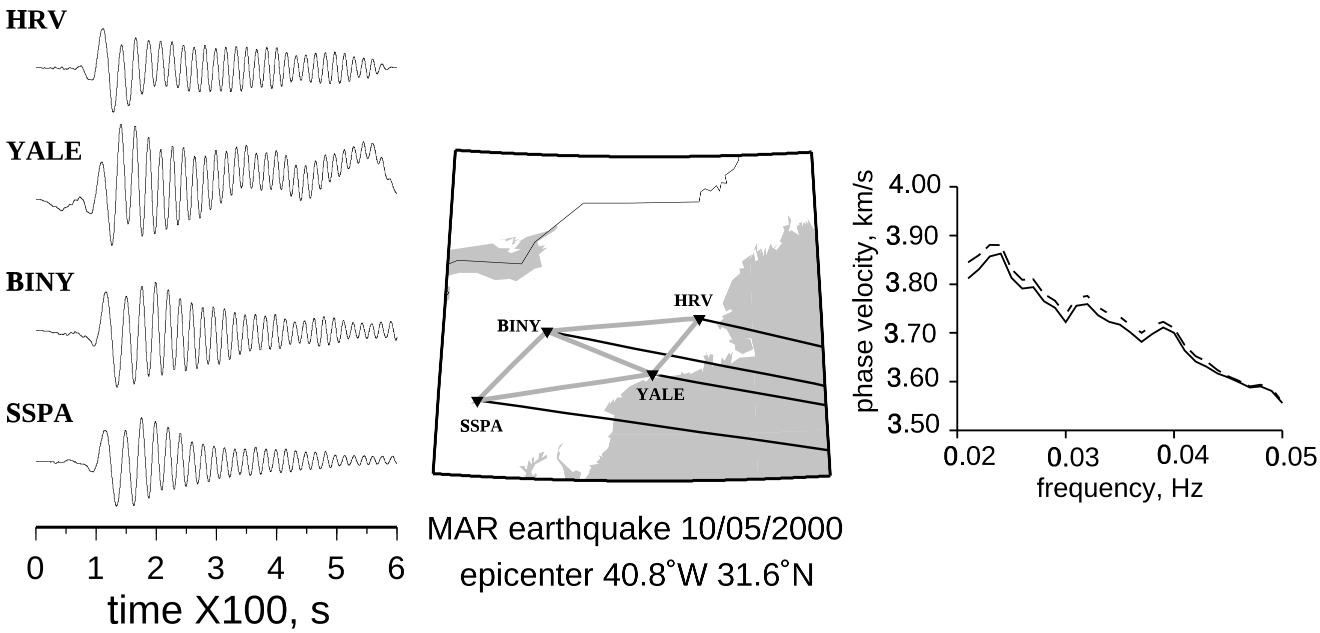

Figure 5. (left) Well-dispersed Raleigh wave from a Mid-Atlantic Ridge earthquake observed on four vertical-component broadband stations in Northeastern US. (middle) Map showing four stations (HRV, YALE, BING, SSPA), which define southern and northern trianges. (right) Local estimate if phase velocity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

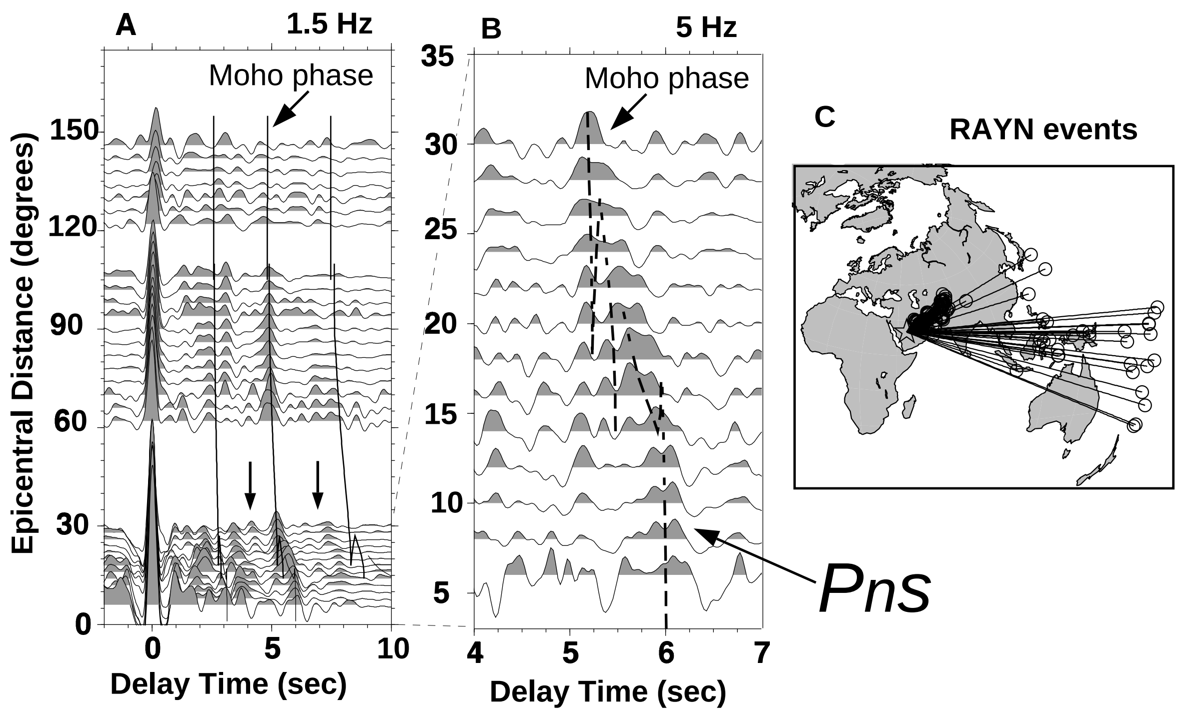

Figure 6. A) Radial receiver functions (RF) computed for GSN station RAYN (Ar-Rayn, Saudi Arabia), averaged in epicentral-distance bins with 50% overlap (10° bins for 60°⩽Δ < 160°; 2° bins for 5°⩽Δ <30°). Results for broadband data (channel BH, 20 sps) are shownfor eastern backazimuths, with RF spectra 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.