Project Description

Introduction and Objectives. The Bahamas Islands (Figure 1) are a carbonate platform that extend from the North American continental margin near Florida southeastward toward Hispanola (see review by Sheridan et al. 1988). Their origin is known to postdate the initial rifting of Africa from North America during the Mesozoic, as they 'get in the way' of plate tectonic reconstructions of Gondwanaland. Furthermore, their subsidence is consistent with an initial thermal pulse occurring at that time (Freeman & Ryan 1987). Surpassingly, however, the actual mechanism of their creation remains uncertain. The great thickness of carbonate sediments has limited direct sampling of the crystalline basement in drillholes, and also obscures the deep crust in seismic reflection surveys. Three hypotheses have been proposed for their origin (Dietz et al. 1970; see also cartoons in our Figure 3):

1. The carbonates rest on highly thinned continental basement;
2. The carbonates rest on an oceanic (basaltic) plateau; and
3. The carbonates rest on normal oceanic crust.

Each of these mechanisms is arguably consistent with the existing data. The problem is that during the initial phase of rifting the thermal uplift would have brought basement of any type close to the sea-surface. Once the carbonate platform became established, its continuation to the present day is merely a question of whether biogenic productivity is fast enough for it to keep up with thermal subsidence.

The thinned-continental lithosphere hypothesis has arguably the most adherents. There are clear analogues elsewhere along the margin, such as eastern Canada, where stretching has reduced the continental crustal thickness by a factor of two (Keen & Barrett 1981) and where carbonate deposition is known to have occurred during the early phases of rifting (though not thereafter). The subsidence data is compatible with a factor of 2-2.5 stretching in the Bahamas (Freeman & Ryan 1987).

Adherents of the basaltic plateau hypothesis can draw upon the many island chains related to hot spot activity (e.g. the Azores, Ongtong Java, etc.) as analogues. Depletion upon partial melting would cause mantle velocities to be anomalously high beneath such a volcanic feature, and indeed the continent-scale long-period waveform inversion of Van der Lee & Nolet (1997) does show a localized shear velocity high in this region (figure 2).

Links have also been proposed between this hypothesized plateau and the voluminous (3 million cubic km) basaltic volcanism that occurred during the early Jurassic along eastern north America (e.g. the Palisades Sill and other parts of the US Atlantic Margin Large Igneous Province). The strike of many of the dikes, for instance, are compatible with a center of volcanism near the Bahamas (an idea associated with the name of R. Dietz). On the other hand, Holbrook and Kelemen (1993) reject such a link on the basis of the Igneous Province's along-strike petrologic homogeneity, which they feel is incompatible with a point-source origin.

Finally, adherents of the normal basaltic crust hypothesis can draw upon the effects of intense clastic sedimentation that occurs in some narrow, newly-formed ocean basins (e.g. the Gulf of California), to provide a mechanism for making the sea initially shallow enough for biogenic carbonate deposition to begin.

The passive seismic experiment that we are proposing will be able to distinguish between these alternative models for the origin of the Bahamas. Through a combination of receiver functions, surface wave dispersion and regional body wave traveltime analysis, we will measure the seismic velocity structure of the crust, and definitively determine whether it has continental or oceanic affinities, and whether it is thick or thin. Other passive seismic techniques, including transverse shear wave splitting and teleseismic body wave tomography will be used to probe the mantle beneath the Bahamas.

Answering the ‘origins question’ is only the starting point of our proposed work. Regardless of their origin, the Bahamas are an excellent subareal platform that provides long-term “observatory” access to the eastern side of the North American continental margin. They can be used to construct a passive seismic transect for a roughly 1000 km swath outward from the nominal continental margin. When combined with stations on the mainland, they provide excellent coverage of both sides of the continent-ocean margin for studies that require a horizontal resolution of 100-200 km, and depth penetration thought the lithosphere and into the upper asthenosphere.

Of course, the detailed problems that can be addressed will depend on just what the Bahamas are.

Rifted continent origin: One important question than can be addressed is the way in which strain departs from the very simple, uniform (pure-shear) stretching models first proposed by McKenzie (1978), and in particular the role of simple shear occurring in thin, subhorizontal mantle shear zones (Vissers et al. 1995) like those imaged by seismic reflection beneath the North Sea (Flack et al. 1990) and Nova Scotia (Keen et al. 1991). Our passive experiment provides several types of data relevant to the question. First, transverse-component receiver functions have proved effective in imaging thin (~10 km) highly anisotropic mantle layers that would be the seismic expression of shearing (Levin & Park 2000; see also figure 4 of this proposal). Should these be detected, we would be able to map their geographical extent, and depth, as well as infer the orientation of strain that formed them. Second, radial receiver functions have proved effective in detecting subhorizontal structures within the mantle, whose lateral continuity and depth variations would reflect the amount and type of thinning. Finally, shear wave splitting measurements would quantify the overall strain directions.

Shear wave splitting data for the New York - New England part of eastern US indicates that two distinct layers, with different parameters of seismic anisotropy, are present in the upper mantle there (Levin et al. 1999; Levin et. al. 2000a, Levin et. al. 2000b, see also figure 6 of this proposal). The layers are 50-100 km thick, continuous across the ~750 km wide region and show only minor regional variation in thickness and/or anisotropy strength. The upper layer is associated with the stable continental lithosphere, and represents stain from past tectonic activity, while the lower layer is more likely to reside in the asthenosphere. We will search for similar layering of upper mantle fabric beneath southeastern US and the Bahamas. Should a lithospheric layer be present, its thickness variations may be related to the amount of stretching that has occurred.

Sheridan et al. (1988) notes that Klitgord et al.’s (1984) magnetic map shows the Blake Spur magnetic anomaly extending into the western Bahamas (albeit with a left-lateral offset of about 100 km). Insofar as this anomaly is known to be on normal oceanic crust, it may indicate that only the western part of the Bahamas are continental. We will specifically address whether any sharp changes in crustal structure occur in this (or other) parts of the Bahamas, using the imaging techniques.

Basaltic plateau origin: Basaltic plateau crust can be distinguished from thinned continental crust of the same thickness on the basis of mid to lower crustal seismic velocities, which are 10-15% higher for basaltic crust than continental crust. Both the radial receiver function and regional wave traveltime data will provide information on this structure (as well as determine crustal thickness). The surface wave analysis and teleseismic body wave tomography will also provide an image of upper mantle seismic velocities, with a resolution of ~100 km. This is considerably better than the 300-500 km resolution achieved by Van der Lee and Nolet (1997) in their continental-scale inversion, and will allow to define the shape of the high-velocity patch that they identified. In particular, it will provide better constraints on the depth distribution and shape of the high-velocity feature, which will help in distinguishing a plume-related origin from other possible sources. The possibility that it is actually associated with relic subduction on the neighboring, but defunct Cuban subduction zone to the south will need to be carefully examined. The sense of underthrusting (i.e. north or south) on this subduction zone is still debated (see below). Only northward subduction would produce a velocity anomaly under the Bahamas. Teleseismic tomography will be used to identify any slab-shaped features associated with it.

Oceanic crust origin: In this scenario, normal, thin (6-8 km) oceanic crust would be isostatically depressed by a thick (10-15 km) load of syn-rift and carbonate platform sediments. We would rely mostly upon receiver functions to detect the buried oceanic crust. Presence of normal oceanic crust under the Bahamas might at first seem as the least interesting of the scenarios, but we suggest that this is not actually the case:
It is tempting to imagine the oceanic lithosphere of the Atlantic as uniform and boring, but actually, the little data that exist suggest just the opposite. The part of the western Atlantic ocean that appears on Van der Lee and Nolet's (1997) tomographic image (our figure 2) is quite heterogeneous - at least as heterogeneous as, say, the eastern US. High resolution tomography would give a better sense of the nature of this heterogeneity (i.e. its lateral scale and depth extent), which might give clues to its origin. Very little information is available about the thickness of the seismically anisotropic layer in the oceanic lithosphere that forms when olivine crystals are aligned by the corner flow at the ridge. An exception is the vicinity of East Pacific Rise, where the MELT experiment demonstrated significant difference between the Pacific and Nazca plates (Wolfe & Solomon, 1998), and also suggested that sub-lithospheric material must contribute to the observed shear-wave splitting. Similarly, very little data is available on whether subhorizontal internal layers exist within the oceanic mantle lithosphere, that might, for instance, be fossil remnants of the mantle melt zone (say at 40-50 km depth). Presence of such layers (e.g., a ~80 km deep discontinuity) was suggested for some oceanic regions (Gaherty et al. 1999). A combination of surface wave analysis, receiver functions and shear wave splitting observations should give us a good idea about the vertical distribution of seismic velocity, sharpness of interfaces, and presence and distribution of strain-induced fabric.

Previous work. Much work was done on the Bahamas during the golden age of plate tectonics (say 1965-1980), but it has been only infrequently studied since. Space considerations limits us to a very brief review of the major results.

- Regional surface wave dispersion is consistent with crust of intermediate thickness (Sheridan, 1972).

- Magnetic anomalies, such as M25, have been identified just north of the Bahamas, but truncate just north of the Bahamas escarpment, where they intersect a southeast trending magnetic lineament that some researchers identify as a fracture zone (called the Bahamas fracture zone) (Bracey, 1968; Klitgord et al. 1984).

- The Blake spur magnetic anomaly seems to extend into the western Bahama Platform, but with a left-lateral (i.e. eastward) offset of about 100 km (Klitgord et al. 1984). This may indicate that the crust there is oceanic, and that the continental margin is to the west.

- The Great Isaac well in the eastern Bahamas sampled a 5.4 km thick shallow-water carbonate sequence, underlain by volcanoclastic sediments (Tator and Hatfield, 1975). The volcanoclastic rocks are of unknown age, but may correlate with similar, Triassic age "basement" rocks in Florida.

- Multichannel seismic surveys show that the carbonate/volcanoclastic boundary is at a depth of 5-6 km in the eastern Bahamas, and appears to be cut by normal faults (Seridan et al. 1981; Ladd & Sheridan 1987). The volcanoclastics are often tilted by the faulting.

- Subsidence history, as deduced carbonate stratigraphy, is consistent with thermal subsidence. Simple McKenzie-type rifting models give a factor of 2-2.5 stretching (Freeman and Ryan, 1987).

- The Bahamas were extensively faulted during the late Cretaceous to early Tertiary, possibly due to interaction with the now-defunct Cuban subduction zone (Mullins and Sheridan, 1983). The sense of subduction is uncertain. Patterns of thrusting in Cuba indicate subduction to the south (Sheridan, 1988), but Malfait and Dinkleman (1972) indicate subduction to the north. Sheridan et al. (1988) suggest that a north-to-south polarity-reversal might have occurred.

Proposed Seismic Experiment. *Deployment.* We propose to deploy 10 broadband seismic stations on the Bahamas, 4 on Florida (Figure 5). When taken together with existing stations in mainland US and Puerto Rico, this will allow imaging of a ~2000 x 200 km swath from Georgia and Florida, across the nominal continental margin to the easternmost Bahamas. We plan to operate the array for a period of 18 months, which is sufficient to record a teleseisms from a wide range of azimuths and regional earthquakes from the Leeward Antilles, Cayman trough, Mid-Atlantic Ridge and southeastern US (Figure 5).

Logistics. We propose to use standard equipment available from the PASSCAL pool. Current estimates of instrument availability (available at www.iris.edu) show that we can reasonably expect getting instruments by during the fall of 2001. Both W. Menke and V. Levin used PASSCAL equipment previously, in conditions somewhat more challenging then those expected in the proposed area (Menke-Iceland, Levin - Kamchatka).

Given high degree of development and the southerly latitude of the region we do not expect problems in obtaining power for our equipment, from local AC grids in combination with solar power. Primary concerns for the hardware will be water and wind-proof installations and security, which we will address according to the available site conditions.

Data retrieval and maintenance of the equipment will be performed by LDEO-based personnel on a periodic basis. In the present form, PASSCAL portable seismic observatories require minimal maintenance once properly installed. Large capacity of modern hard disks make it possible to collect data for many months. We plan to visit each site at least every 5 months, with contingency service budgeted for emergencies.
Data preprocessing and archiving will be performed at LDEO, using a dedicated computer and a 10 Terabyte MassStore facility.

Proposed Timetable:

Year 1: Jul: Find sites for stations
Oct: Install stations
Mar: Service stations, retrieve and archive data
Apr: Begin preliminary analysis of data
Year 2: Jul: Service, retrieve and archive data
Aug: Continue preliminary analysis of data
Nov: Service, retrieve and archive data

Year 3: Jan: contingency plan, service only if necessary
Mar: Remove stations, retrieve and archive data
Apr: Final analysis of data
Jun: Interpretation of results

Sources of Data. Natural seismic activity of the Earth will be the primary source of data. Figure 5 shows distribution of earthquakes over a two-year period (1997 & 1998). On a global scale, events of Mb>6.5 will provide good illumination from a variety of directions - a condition for successful application of such techniques as shear wave splitting, receiver function analysis and teleseismic body wave tomography. Moderate-size seismically of the Caribbean will compliment tomography and receiver function analysis, and will also serve as a source of higher-frequency surface waves for studies of the crustal and upper-mantle structure. Seismic activity under the island of Hispanola, conveniently located at the southeastern end of the proposed array, will be used for probing the upper and middle crust with regional phase propagation techniques.

Data Analysis Methodology

Receiver Function Analysis. Isolation and analysis of P-S mode-converted phases within the coda of teleseismic body waves - the receiver function (RF) method - will be the primary tool to probe the vertical structure 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. We will use both “Radial” and “Transverse” receiver functions. The Radial receiver function brings out P-SV conversions from layering (or zones of high gradient) beneath the receiver. The Transverse function brings out P-SH conversions that depend upon the degree of anisotropy of the layers (or zones), and/or on the dip of the converting interface.

One of us (Levin) has submitted a paper (Park & Levin 2000) that describes a greatly improved RF analysis algorithm based on spectral coherence estimates. Figure 7 shows an example of receiver functions computed via this algorithm, using 2 years of data from a global seismic station RAYN (Ar-Rayn, Saudi Arabia). Coherent phases marked on the plot represent a crust-mantle transition (at 4.75 sec), and a deeper feature of the impedance profile (at ~8 sec). Both phases possess strong transversely-polarized components, and show little move out with epicentral distance, suggesting near-horizontal impedance contrasts within anisotropic medium (Levin and Park, 1997; 2000). Note the continuity of converted-phase signatures throughout the epicentral distance range, including RFs computed from body waves interacting with Earth’s core (PKP, Pdiff). These seismic phases are rarely used in RF estimation, but the new algorithm appears to yield excellent results when frequency-dependent signal-to-noise ratios are taken into account. Our experience with observations from Arabia, the Urals and Russian Far East (Levin & Park 1997, 2000; Park & Levin 2000) argues in favor of including these data, as well as data from distances as close as 10 degrees. An expanded range of observed phase velocities simplifies such basic tasks of RF analysis as discrimination of multiples and identification of interface dips.

The location of the proposed array will allow us to construct epicentral-distance profiles like that shown in Figure 7 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 variations of seismic velocity field along the array as it goes from the stable continental

interior, across the passive rifted margin and through the Bahama platform. We expect 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 high-velocity anomaly in the region sampled by our proposed array. We expect 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, which are situated near the western edge of this continental margin (Levin et al. 1995; Levin et al. 2000). We are confident that the new dataset that crosses the continental margin can achieve a similar resolution. We also have developed a new code (available at www.ldeo.columbia.edu/users/menke/software/) that uses a 3D tetrahedral basis to represent the earth's seismic velocity field and which performs multiple iterations velocity inversion.

Shear Wave Splitting. In his previous collaborative effort with Levin, Menke performed a joint analysis of shear wave splitting and traveltime delays in the New York and New England region (Levin et al. 1999, Levin et al. 2000; 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 6). This directional dependence is key to detecting several layers with distinct anisotropic properties. They developed both a data analysis technique capable of making apparent splitting direction measurements from single shear-polarized phases (S, SKS, PKS), and a modeling method capable of determining the layer parameters from the observations. These methods will be employed in the current study.

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, using a pair of stations along the surface wave path or a triangular array. Moderate seismicity present at the southeastern end of our proposed deployment will facilitate the use of the two-station technique. Width of the Bahama archipelago will allow us to deploy instruments in a broad swath. By forming small triangular subsets of the array, we will constrain vertical profiles of shear velocity for patches with lateral dimension of ~100km, which will be complimentary to the tomographic imaging work.

Regional Wave Propagation. Regional seismicity (e.g. within the western North Atlantic Basin, Mid Atlantic Ridge, and the Caribbean, 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 lower crust and the uppermost mantle - regions that are poorly resolved by techniques like teleseismic tomography.

Project Management. William Menke will be responsible for the overall conduct of the project and for its timely completion. The field team will consist of Menke, seismologist Vadim Levin, a postdoc, an engineer, a grad student funded on the project and several other LDEO student volunteers. Menke and Levin have extensive prior experience in conducting seismological field experiments. All project participants will be involved in all aspects of the data analysis, with Menke spearheading elements of the analysis that involve tomographic inversion and Levin elements of the analysis that involve receiver functions and splitting.

Use of Facilities. The proposal requests use of 14 broadband seismometers from the IRIS/PASSCAL pool for a period of 18 months. A request to use these facilities has been filed with IRIS.

Dissemination of Results. We will submit all data to the IRIS DMC within one year 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). 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.

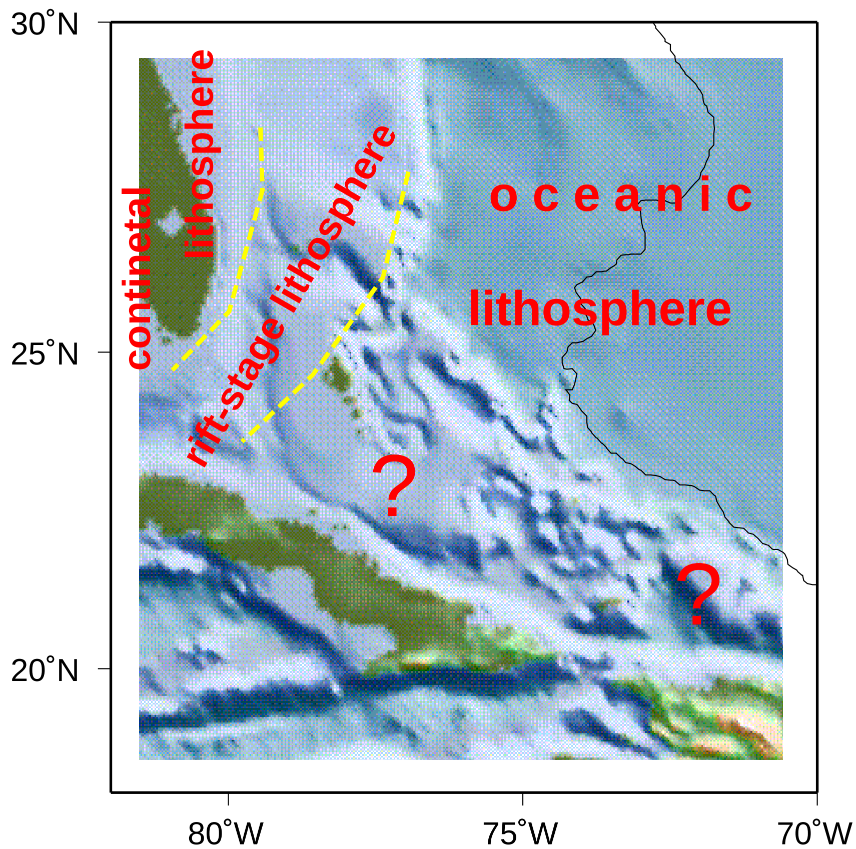


Figure 1. Bathymetry of the Bahamas and lithoshpere types inferred from previous studies. Depth of 5000 m is shown by the solid line. Location of rift-stage lithosphere as proposed in Sheridan et al,1988.

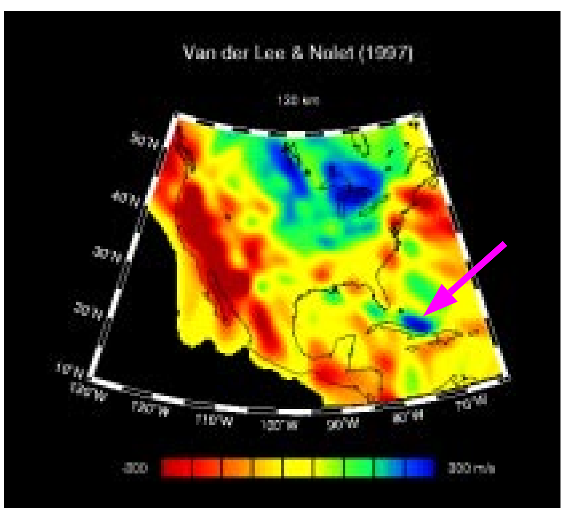


Figure 2. Shear wave velocity distribution under North America at 130 km depth (from van der Lee & Nolet, 1997).
Large fast velocity anomaly (arrow)
is seen under the southeastern part of the Bahama archipelago.

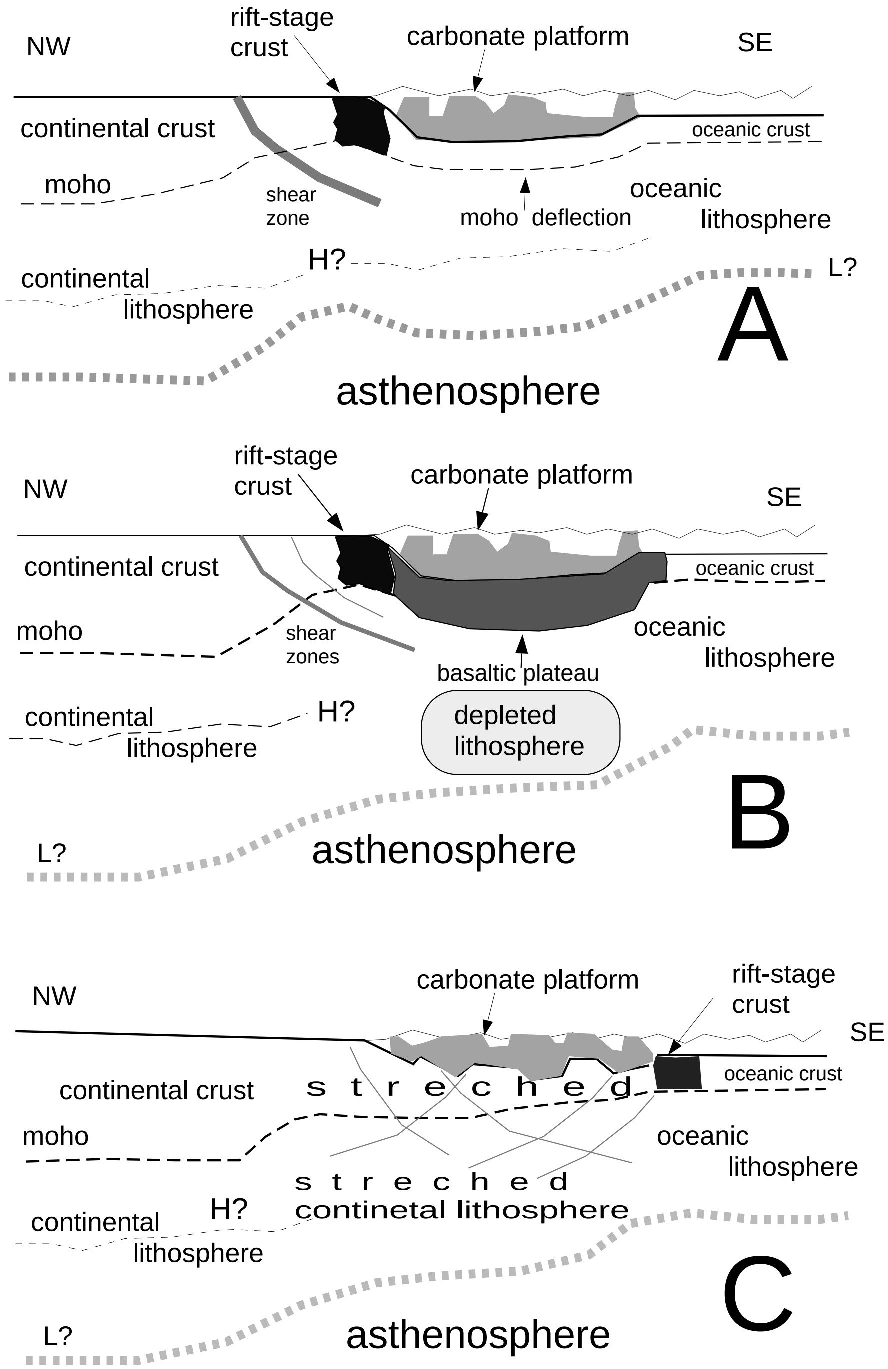


Figure 3. Schematic representation of three possible tectonic scenarios for Bahama Platform: A - normal oceanic crust; B - basaltic plateau; C - stretched continetal lithosphere.

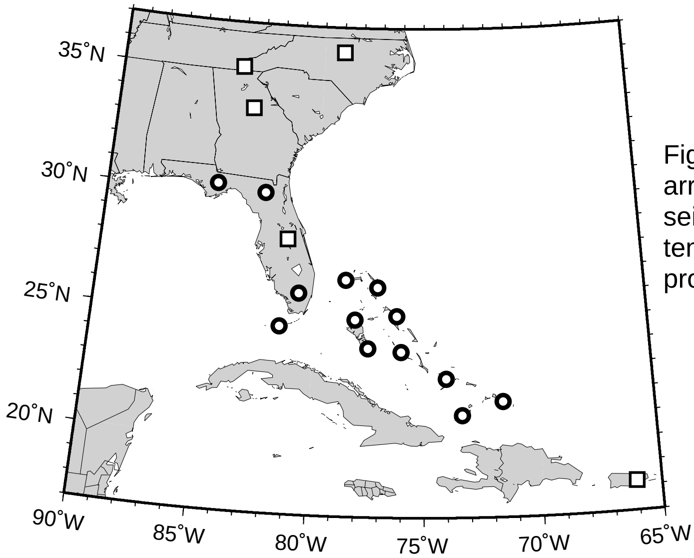
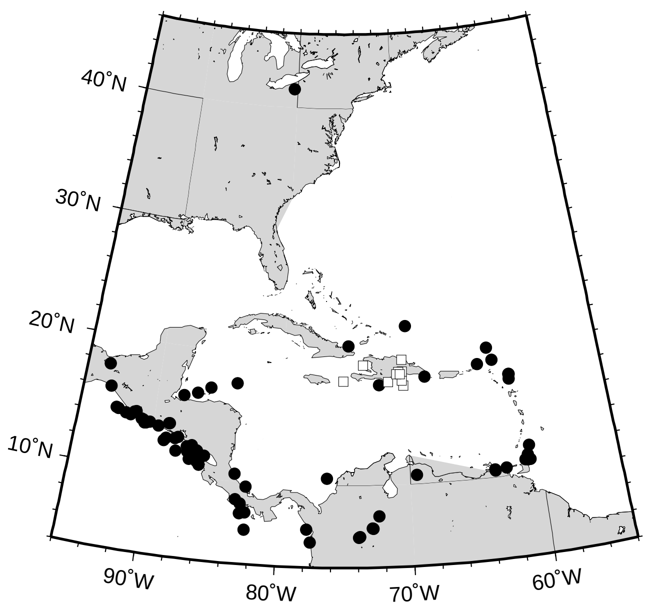
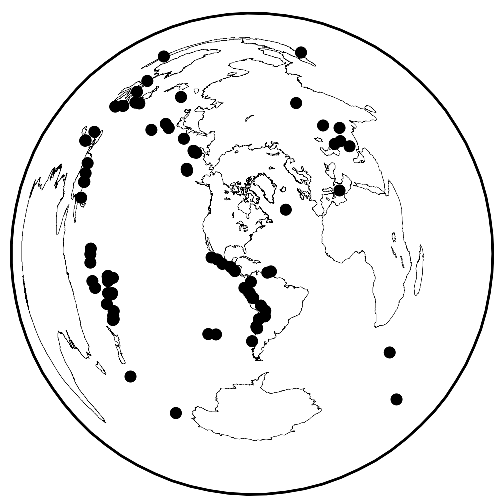


Figure 4. Schematic map of the proposed array. Squares show permanent broad-band seismic observatories, circles indicate tentative locations for the nodes of the proposed temporary array.

Figure 5. Seismicity during 1997-98





Mb>6.5

Mb>5 earthquakes within 20˚ from Bahamas (circles)
5>Mb>4 earthquakes in Hispaniola (squares)

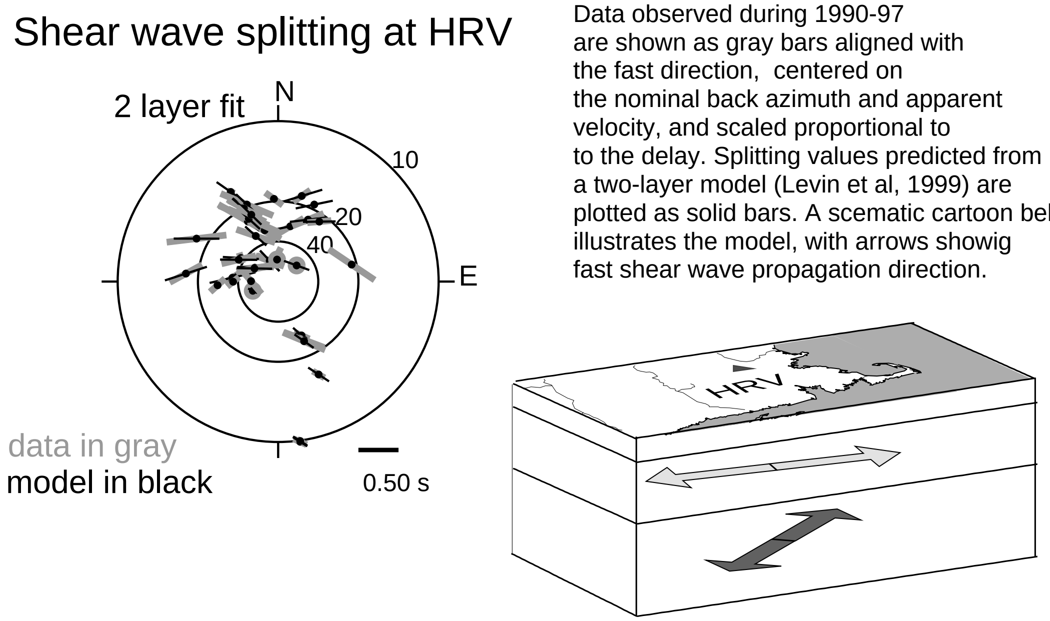


Figure 6. Shear-wave splitting observations and modeling at GSN station HRV (Harvard, Massachusetts). Data observed during 1990-97 are shown as gray bars aligned with the fast direction, centered on the nominal back azimuth and apparent velocity, and scaled proportional to to the delay. Splitting values predicted from a two-layer model (Levin et al, 1999) are plotted as solid bars. A scematic cartoon below illustrates the model, with arrows showig fast shear wave propagation direction.

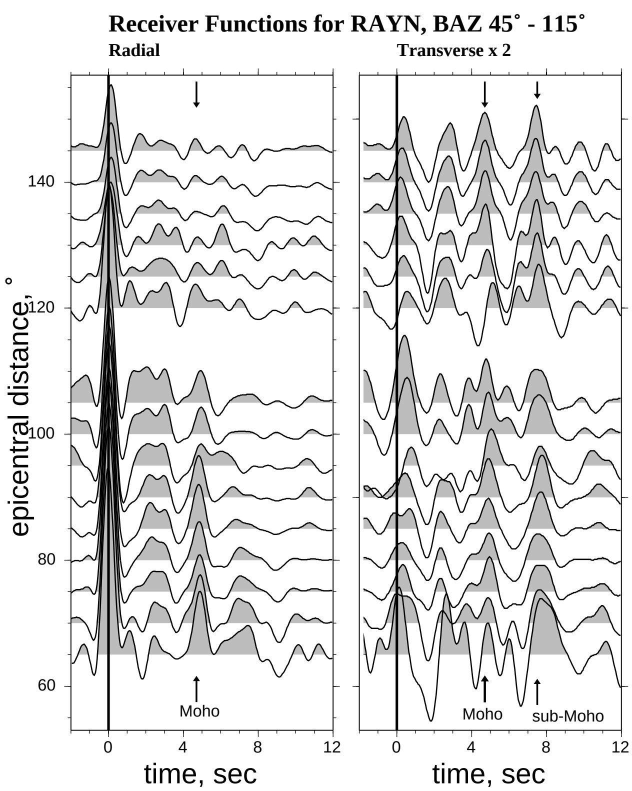


Figure 7. Composite receiver functions computed for GSN station RAYN (Ar-Rayn, Saudi Arabia) using estimates of spectral coherence. Arrows mark converted phases from the crust-mantle transition, and from another feature ~70km deep (Hales discontinuity?). The later is seen predominantly on the transverse component. Note the continuity of converted-phase signatures throughout the epicentral distance range. Modeling these observations, Levin & Park (2000x) infer zones of seismic anisotropy ~10km thick at the Moho (~40km) and at ~70 km, that likely represent relict shear zones formed during the assembly of the Arabian Shield.