USGS/NEHRP Final Technical Report:

Grant Award Number: G09AP00070

Estimating the lower limit of the seismogenic zone and rates of aseismic slip on the Puerto Rico Trench Megathrust using focal mechanisms and repeating earthquakes

Project Period: 05/18/2009 - 05/17/2010

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Abstract

An accurate determination of the earthquake hazard which the Puerto Rico seismic zone presents to population centers in the American Caribbean depends on an accurate location of the main plate interface, or Puerto Rico megathrust. Previous researchers have developed 1-D P-wave velocity models of the region and have improved our understanding of the seismotectonics. However, remaining large station delays and shot mislocations suggest that a 3-D model is necessary for a precise location of events. Of course focal mechanisms can only be well-determined with accurate locations and properly calculated take-off angles. Therefore, this project developed a 3-D P-wave velocity model using shots and blasts, distributed throughout a 200 km long segment of the subduction zone. More than 350 shots and blasts were recorded at numerous land stations providing more than 2100 arrivals and therefore a large region with good ray coverage.

Simul2000 was used to develop the 3-D model. Results show a significant improvement factor of 3) in rms over simple 1-D models, and demonstrate a clear southerly dipping surface with Vp in the range expected for oceanic crust at depths ranging from 10 to 30 km. This appears to be the crust of the North American Plate subducted at the Puerto Rico Trench. This dipping layer of crustal velocities is lost at about 30 Km depth, apparently due to changes in the physical properties of the crust (basalt to eclogite transition). The region east of about 64.6°W is anomalous in that the dipping layer with crustal velocities is not observed, being replace by higher Vp more consist with upper mantle velocities. The anomalous region lies along the down dip (SE) extension of the Main Ridge, a bathymetric high entering the subduction zone. This Ridge has an origin similar to the Barracuda and Tiburon Ridges of the Northern Lesser Antilles. They were formed by transtensional and compressional phases of NOAM-SOAM motion. The Tiburon Ridge is characterized by a near absence of oceanic crust, and an uplifted mantle section, probably an analog to what is observed along the Puerto Rico subduction zone east of 64.6°W.

Several hundred well-observed earthquakes were relocated using the 3-D model. Two distinct groups of earthquakes lies significantly off the main down going zone and are thought to represent seismic activity on intraplate faults, one in the overriding and one in the downgoing plate.

Introduction

The densely populated islands of the US Caribbean lie within a well-defined plate boundary zone (PBZ) separating the North American (NOAM) and Caribbean Plates (CARIB, Figure 1). Oblique collision of those Plates is accommodated by sinistral shear and thrusting along the northern and southern margins of the PBZ, which is composed of a series of microplates. The larger plates move more or less east west with respect to each other at about 21 mm/yr, whereas the relative motion of the microplates ranges between 3 and 5 mm/yr Jansma and Matiolli (2005). Relative movement of the microplates results from along strike variations in the forces exerted on them by the

North America and Caribbean Plates. One of those Microplates includes most of the island of Puerto Rico and all but one of the Virgin Islands (Puerto Rico – Virgin Islands Microplate, PRVI) another occupies the eastern part of the island of Hispaniola (Hispaniola Microplate; Figure 1).

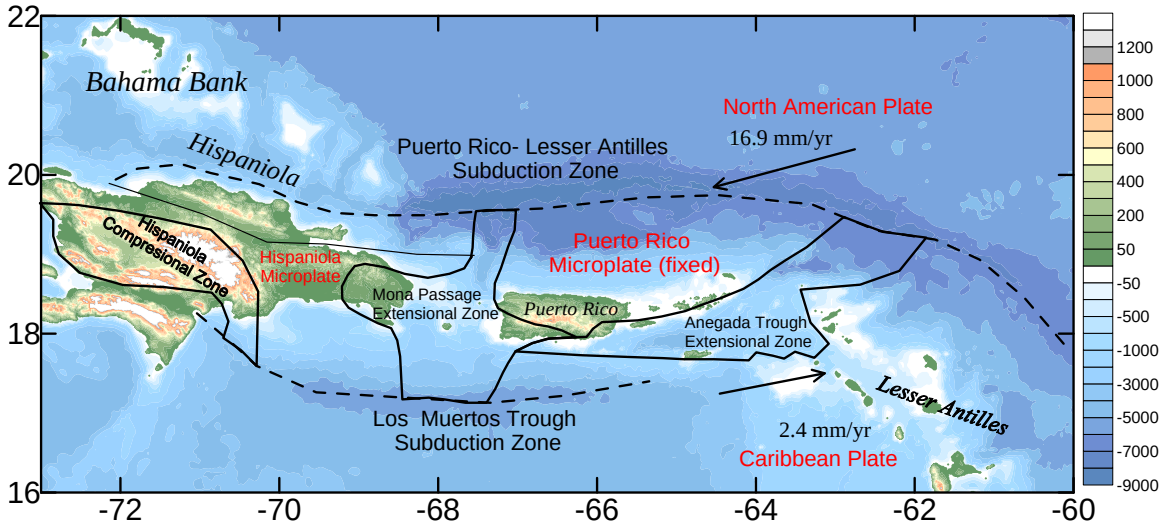

Figure 1. Major Tectonic elements in the northeastern Caribbean. North American and Caribbean plate obliquely converge across the region. A series of microplates buffer the motions of the major plates. The Puerto Rico microplate experiences transtension along its eastern and western edges and oblique convergence along its northern and southern borders. Arrows show direction and rate of plate motions determined by GPS measurements with respect to a fixed Puerto Rico microplate. The focus of this investigation is the development of a 3-D P-wave velocity model for the region from 64°-66°W along the Puerto Rico subduction zone, in order to improve earthquake locations with the final goal of determining details of the geometry of the main plate interface.

Structure and seismicity of the Puerto Rico Megathrust

Some forty years ago Sykes and Ewing (1965) noted the presence of an inclined seismic zone beneath the US Caribbean. That zone emerged to the surface along the Puerto Trench and reached more than 100km depth. Later Molnar and Sykes (1969) demonstrated the existence of an unusual style of motion along the shallower portions of that seismic zone. Focal mechanisms show that motion occurred along a gently south dipping plane but the motion was nearly along strike (oblique thrusting). Ewing et al. (1965) defined the generally morphology of the inner wall of the Puerto Trench noting and east-west ridge just south of the trench axis, and an unusual feature, the Main Ridge, trending oblique across the margin from the island platform to the trench axis. Schell and Tarr (1978) and Murphy and McCann (1979) discussed the spatial distribution of microearthquakes as recorded by local networks. They found clusters of earthquakes near the Virgin Islands near the Main Ridge, and an inclined seismic zones reaching down to 125 km depth. McCann and Sykes (1984) demonstrated that the Main

Ridge was related to fracture zone trends on the downgoing North American plate and hence intimately related to enhanced seismicity near its intersection with the subduction zone, and discussed the relationship between structures on the incoming plate and the occurrence of large earthquakes. Contours for the upper surface of the downgoing North American slab were also defined.

As a result of the relatively slow plate motions in the region, the plate boundary near the US Caribbean has a relatively low level of moderate earthquakes. Local networks began recording microearthquake in 1975. Studies of microseismicity include Asencio (1980), Frankel et al., (1980), Frankel (1982a, b), McCann and Sykes (1984), McCann, 1985, Dillon et al. (1994), McCann (2002). They defined in more detail the location of the main plate boundary and style of faulting on that margin, and the existence of several active faults cutting the island platform.

After these decades of investigations, the general consensus of the scientific community is that the main earthquake threat to the islands of the US Caribbean is large (both major and great) earthquakes rupturing the main plate interface along the Puerto Rico Subduction zone (ten Brink et al., 1999). This is so because those seismic sources are capable to produce relatively frequently earthquakes near magnitude 8, and their relative closeness to the islands (Frankel et al. 1996, LaForge and McCann, 2005). The spatial extent of potential seismic sources (up/down dip limits and along strike barriers) as well as the rate of release of seismic slip, govern event size and repeat times, and are two principal factors determining the actual threat presented by this subduction zone.

Prior efforts to improve event location capabilities in the PRVI subduction zone

Previous velocity models for the Virgin Islands region are few. Officer et al., (1959) presented a several refraction profiles for this part of the island chain. The models were as varied as the tectonics of this complex region. Fischer and McCann (1984) inverted several profiles of earthquakes extending from a certain network station to one of several multi-ton shots above the Puerto Rico megathrust to develop a model for the region north of the main portion of the network. They calibrated with the models with multi-ton shots and found that there were still significant mislocation errors. While some shot mislocations were less than 1 Km, others were as large as 15 Km. Most station delays tended to be small, ±0.2 sec, the stations on Saint Croix in the southern part of the study region consistently had large positive delays which at time reached 1.0 second. These results suggested that shot mislocation and unaccounted for station delays are probably the result of modeling a 3-D structure with a 1-D model.

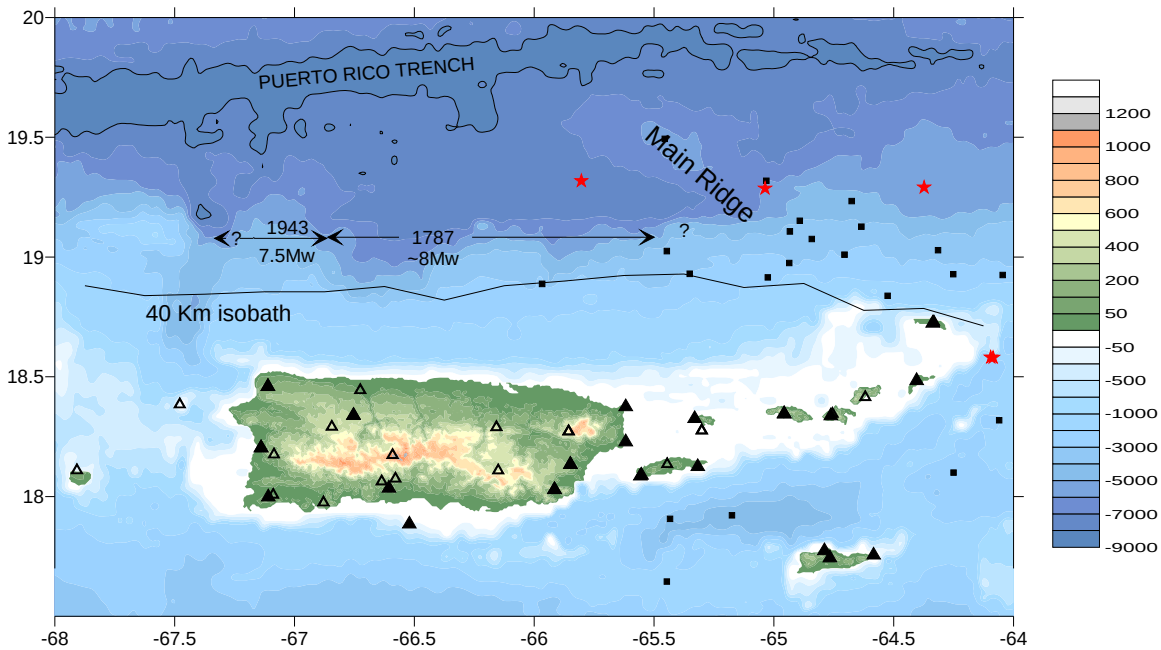

Figure 2. Large earthquakes, local seismic stations, calibration shots and OBS locations. Two significant earthquakes have ruptured the Puerto Rico Subduction Zone, one in 1787, and another in 1943. The 1943 event occurred along a section of the interface probably more strongly coupled than that to the east, where we estimate that 20% of total slip occurs seismically. Triangles are seismic stations Stars are locations of multi-ton shots to be used in calibration of interface event locations. Squares are OBS locations from 1976 and 1979 marine experiments. This investigation focuses on the Puerto Rico Trench megathrust 64-66°W where high quality digital and OBS data as well as calibration shots exist.

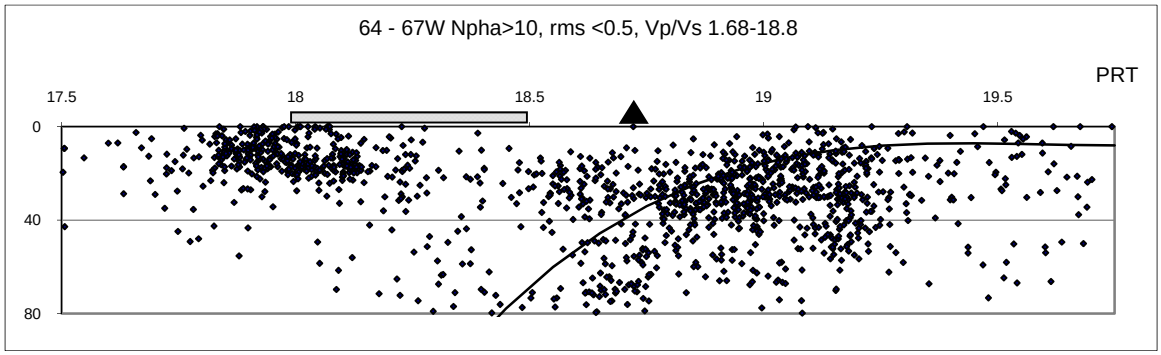

Figure 3. JHD earthquake locations from a previous NEHRP investigation. Vertical Cross section of events along the Puerto Rico - Virgin Islands portion of the Puerto Rico subduction zone from 17.5N to 19.75°N. The curved line is the top of the downgoing North American plate. Grey rectangle from 18.0 to 18.5°N is approximate location of Puerto Rico and most of the network stations. Black triangle at 18.75°N is the northernmost seismic station, virtually on top of the 40 km isobath of the plate interface. PRT is Axis of Puerto Rico Trench. Note significant seismic activity both above and below the main plate contact.

Later, a NEHRP investigation used a distribution of stations and earthquakes that sampled the crust and mantles by the illuminating rays lies generally to the south of the region sampled by McCann and Fischer, so the results are directly comparable. Nevertheless, the average model of Fischer and McCann (1984) was used as a starting model to develop a new 1-D model. Although there is a wide range of shallow crustal velocities in the starting models, 4.5-6.0 km/sec, all four models converged to velocities near 6.0 km/sec for the upper 10km. While there is some variation in the lower crustal velocities and layer thicknesses, all models give a total crustal thickness of 24-32 km with upper mantle velocities in the range 7.5-7.8 km/sec. Event mislocation were estimated using blasts on Saint Thomas. Blast locations determined using the *VELEST* model form an ellipse whose center is just north of that blast site, and with a semi minor axis of about 500 meters from the longitude of the blast site, and semi major axis reaching about 1 km to the south and 2 km to its north.

Development of a 3-D model to improve location capabilities in the PRVI region.

In order to better locate events in the PRVI subduction zone we endeavored to use the best available data and determine a reasonable 3-D P-wave velocity model.

Fortunately, a large suite of controlled artificial sources was available:

Artificial Sources in the Virgin Island Region:

- Blasts from quarry construction on Saint Thomas, origin time unknown, location known.
- Multi-ton and smaller blasts from 1979 marine experiment, origin times unknown, locations known
- Multi-ton shots from 1976 and 1979 marine experiments, origin times known, locations known
- Smaller shots along refraction lines from 1979 marine experiment, origin times known, location known.

Data Preparation

Land Station arrival times for artificial sources on Saint Thomas were already identified. Blast locations determined in a previous NEHRP program.

Land Station and OBS arrival times and locations for multi-ton shots (4) and blasts (1) were previously determined.

Shot origin times and locations for 368 refraction line sources were mostly previous determined, remaining times and locations were determined during this project. The major effort was the determination of land station P-wave arrival times. We were able to produce a dataset with a total of 2,175 arrival times for these artificial sources. Sources ranged from small (1 demolition block) to moderate size (4 haversacks, with 8 demolition blocks per haversack).

At the time of the 1979 experiment when the refractions lines were run, recording at the central recording site consisted of both digital (event-triggered) and analog (continuous-develocorder) types. The digital recording system, being event-triggered, did not record most of these small artificial seismic sources. The develocorder did however record the arrival of P-, S- and converted-waves for most of the shots. For this NEHRP program only the P-wave arrival times were determined. Develocorder microfilm was displayed on a microfilm reader, shot P-wave arrivals identified, and images copied. Paper copies were then scanned, images rectified, and arrival times determined using the programs GIMP and SURFER.

Examples of arrival from weak and strong shots are given in figure 4a, b. The existence of this large suite of seismic wave arrivals at the VI land stations for so many for controlled sources was totally unexpected and will be an extremely valuable resource for future investigations of the PRVI crustal structure and the nature of the subduction zone.

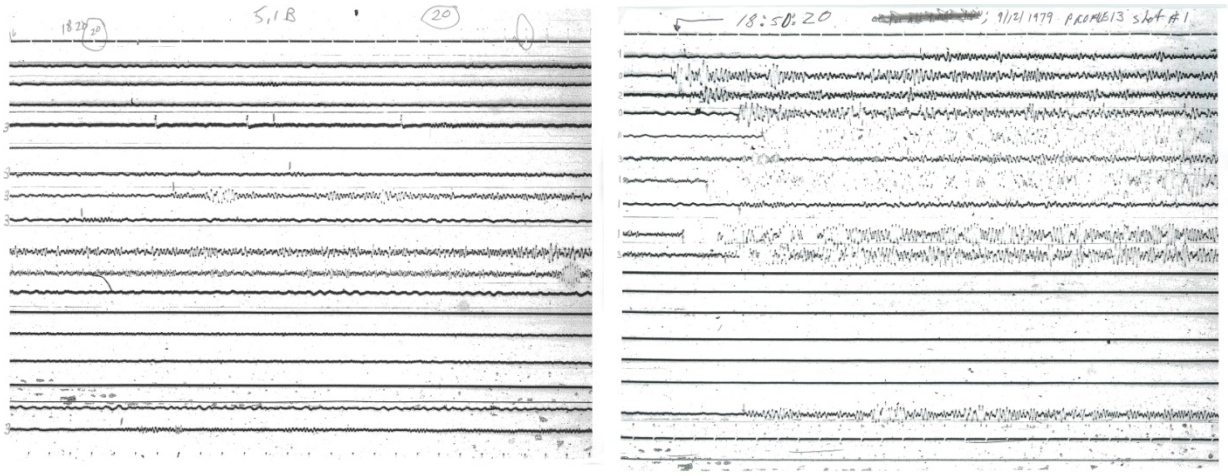

Figure 4a, b a) Develocorder record with 5 P-wave arrivals from shot #1 of profile #5, 5 demolitions blocks. b) Record with 11 P-wave arrivals from shot#1 of profile #13, 4 haversacks, or 32 demolition blocks. Note the clear secondary arrivals on several stations.

Only of small amount of the available OBS data, previously determined arrival times, were used in this program. Hydrophone data was not used.

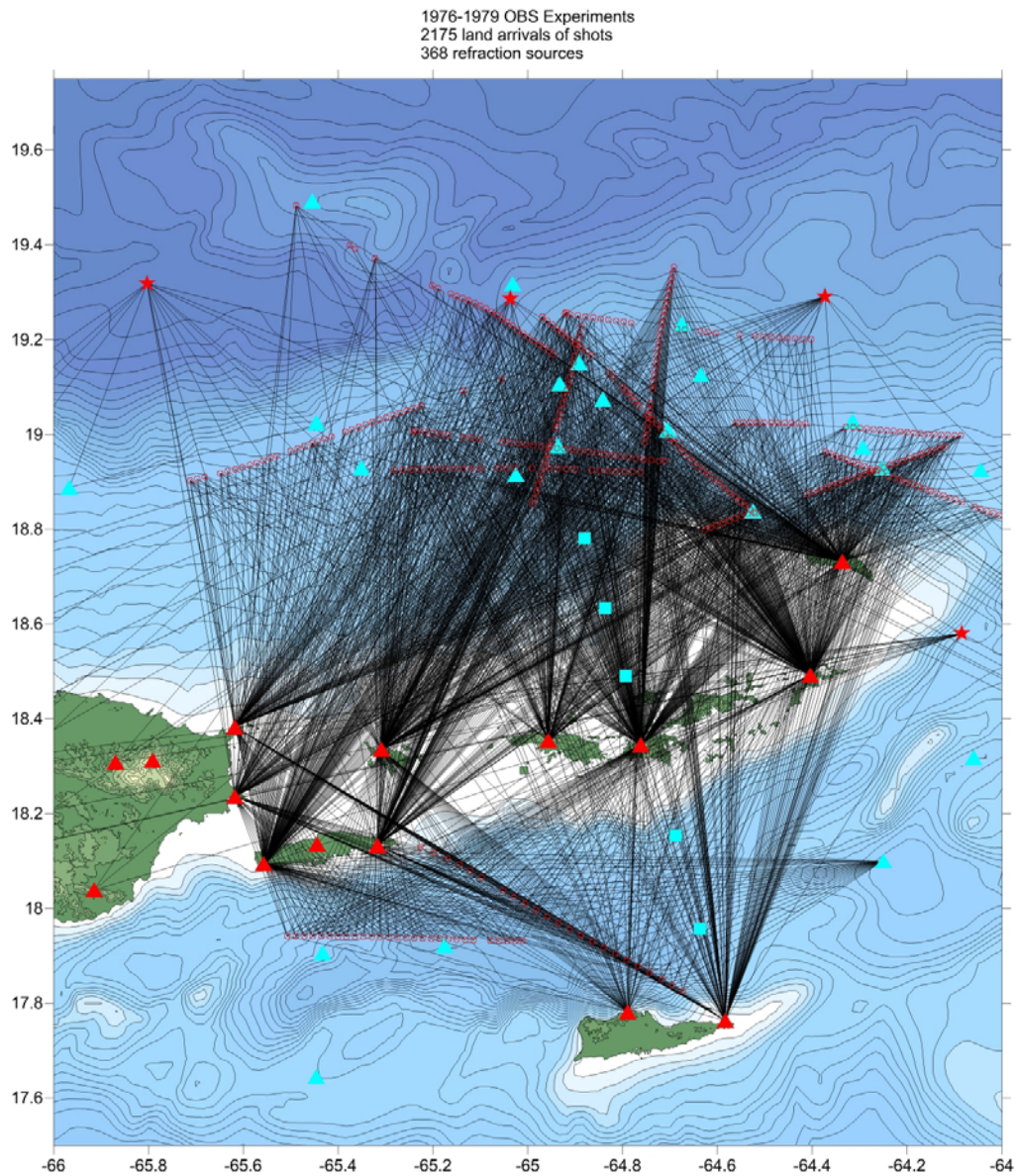

Figure 5. Solid red triangles are land stations. Only data from stations east of 65.8°W were used in this program. Cayan triangles are locations of Ocean bottom seismometers, Cyan squares are hydrophones used to record one of the multi-ton shots (stars). Small circles are location of shots set off as refraction profiles. Lines connect shots and observing stations. This figure indicates extent of ray coverage used to develop a 3-D P-wave velocity model for the region between the shots and the land stations. Most dense ray coverage is in the region to the north of the Virgin Islands Platform from about 18.4° to 19.1°N and 64° to 65.7°W or about 200 km along the PRVI seismic zone. This is the region in a 3-D P-wave velocity model was calculated using *SIMUL2000*. Stations west of 65.8°W and east of 64°W were not considered at this time. The western stations, from the original USGS PR network, were also recorded on develocorder as the LDEO network, so it is very likely that those records, now housed in Puerto Rico, contain valuable arrival times from the larger refraction shots, especially those to the western part of the study area.

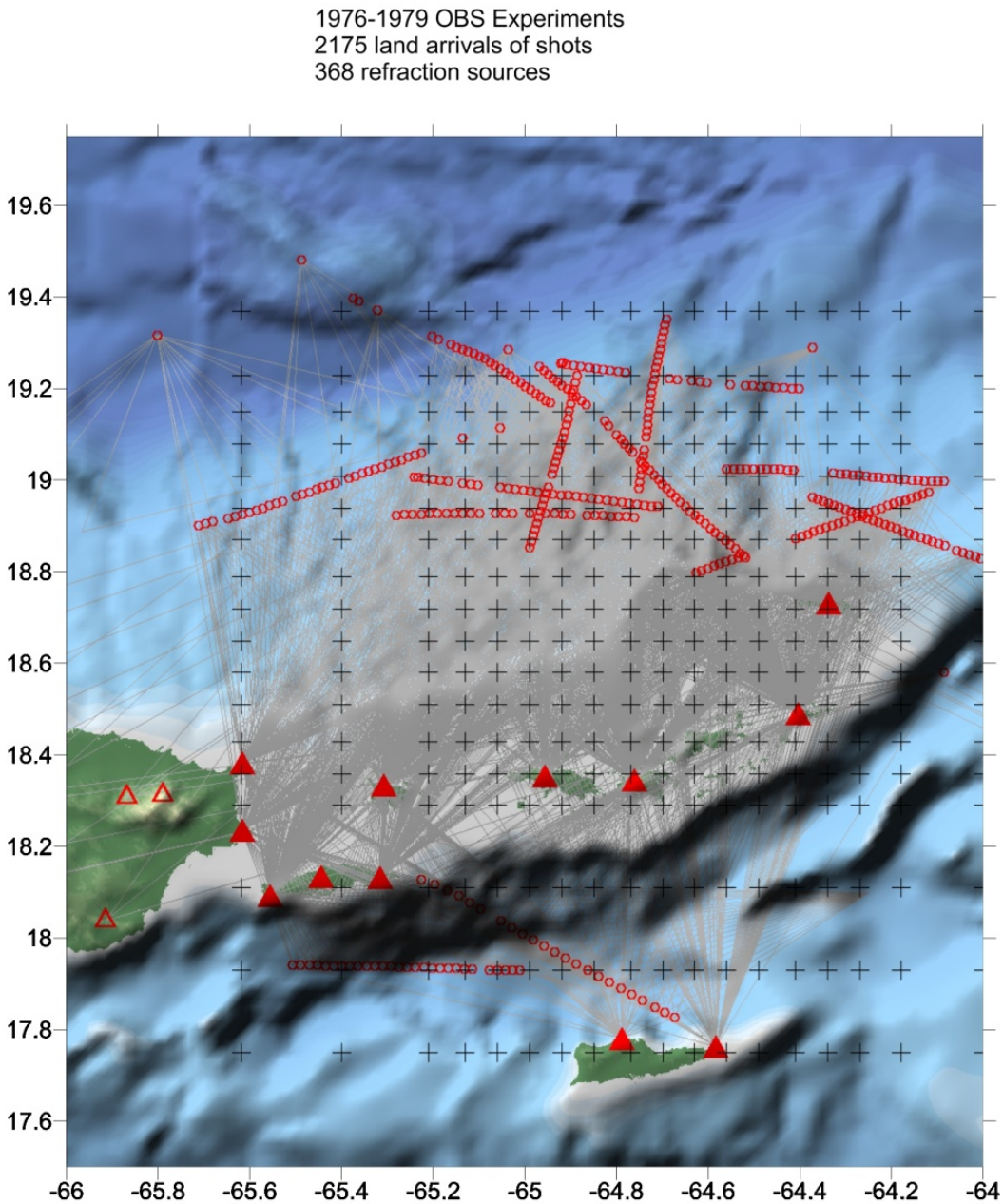

Figure 6. Node distribution (+'s) superimposed on rays (from figure 6) used in 3-D velocity model. Node distances were calculated from 64°W 17.75°N.

Development of 3-D velocity model using SIMUL2000

The program SIMUL2000 was used to determine a 3-D velocity model for the region (Thurber and Eberhart-Phillips, 1999). Because the locations and origin times of 388 sources are known, and the locations of 22 blasts are known, their known parameters were fixed in the inversion process. With the large number of artificial sources, and there being no need to determined their location or time parameters, the nodal distribution was not increased throughout the inversion process. In the region of

main interest, noted above, nodes were spaced every 8 km in the X (longitude) and Y (latitude) directions. In the Z direction (depth) nodes were spaced every 4 km from 16 to 52 km depth. From 1 to 7 km nodes were spaced every km, another node was placed at 11 km depth. The large number of nodes in the shallow region was needed to minimize travel-time errors associated with the water to sediment transition. In the southern region more widely spaced nodes were included so that arrivals from two stations on Saint Croix could be included in the inversion process.

Different initial velocity models were based on the 1-D velocity inversion results of Fischer and McCann (1984), the previous *VELEST* results, and refraction profiles in the region reported by Officer (1959).

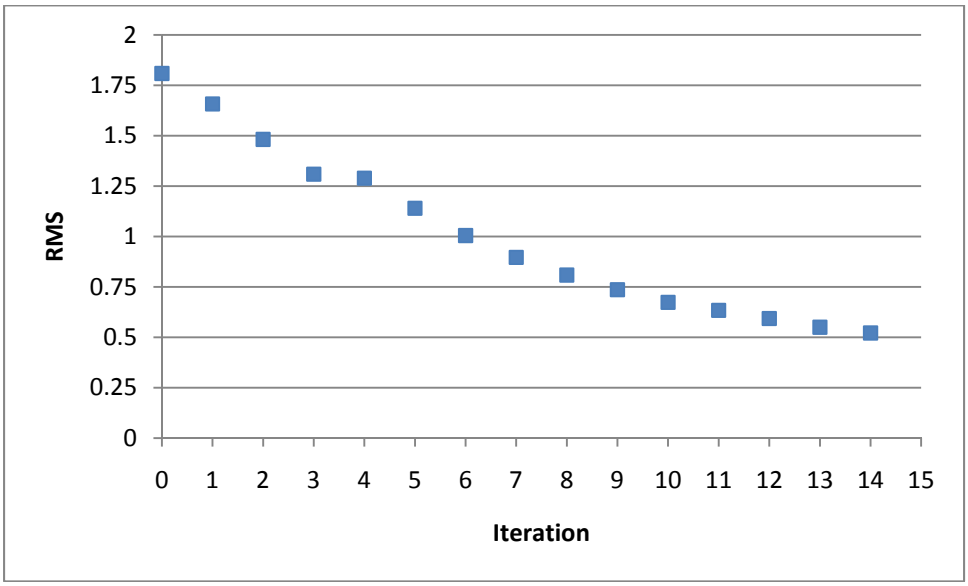

Figure 7. Change in rms per iteration in *SIMUL2000*.Rms was reduced by a factor of 3.

Results

Figures 8-10 present the main results of the velocity modeling. A substantial region is observed, from node distance 50 to 120 km, with crustal velocities consistent with a root to the Virgin Islands arc massif. Velocities throughout much of the region (node distance 75 to 150 km) are consistent with the subduction of normal oceanic crust at the Puerto Rico Trench and dipping southerly beneath island platform. However, velocities in the eastern region are anomalously fast.

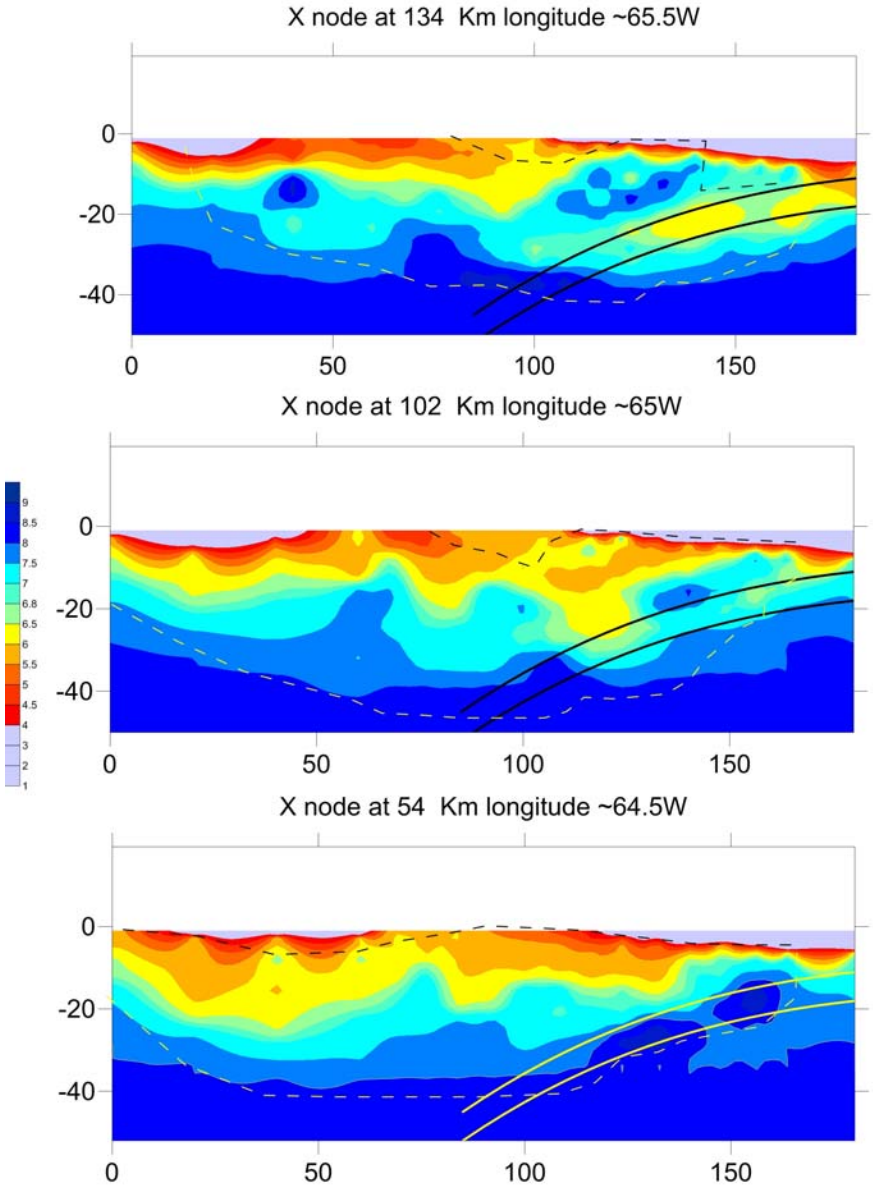

Figure 8. N-S Vertical cross-sections along the eastern central and western portions of the modeled region. North is to the right. Two curves indicate the location of presumed oceanic crust of the southerly dipping North American Plate. Note that in the western and central regions (upper and middle panel) a southerly dipping region with velocities similar to that expected for oceanic crust is found, whereas the eastern region is dominated by high P-wave velocities more typical of mantle. Dashed lines show upper and lower limits of region with DWS greater than 5 and therefore bound the region considered in the inversion process.

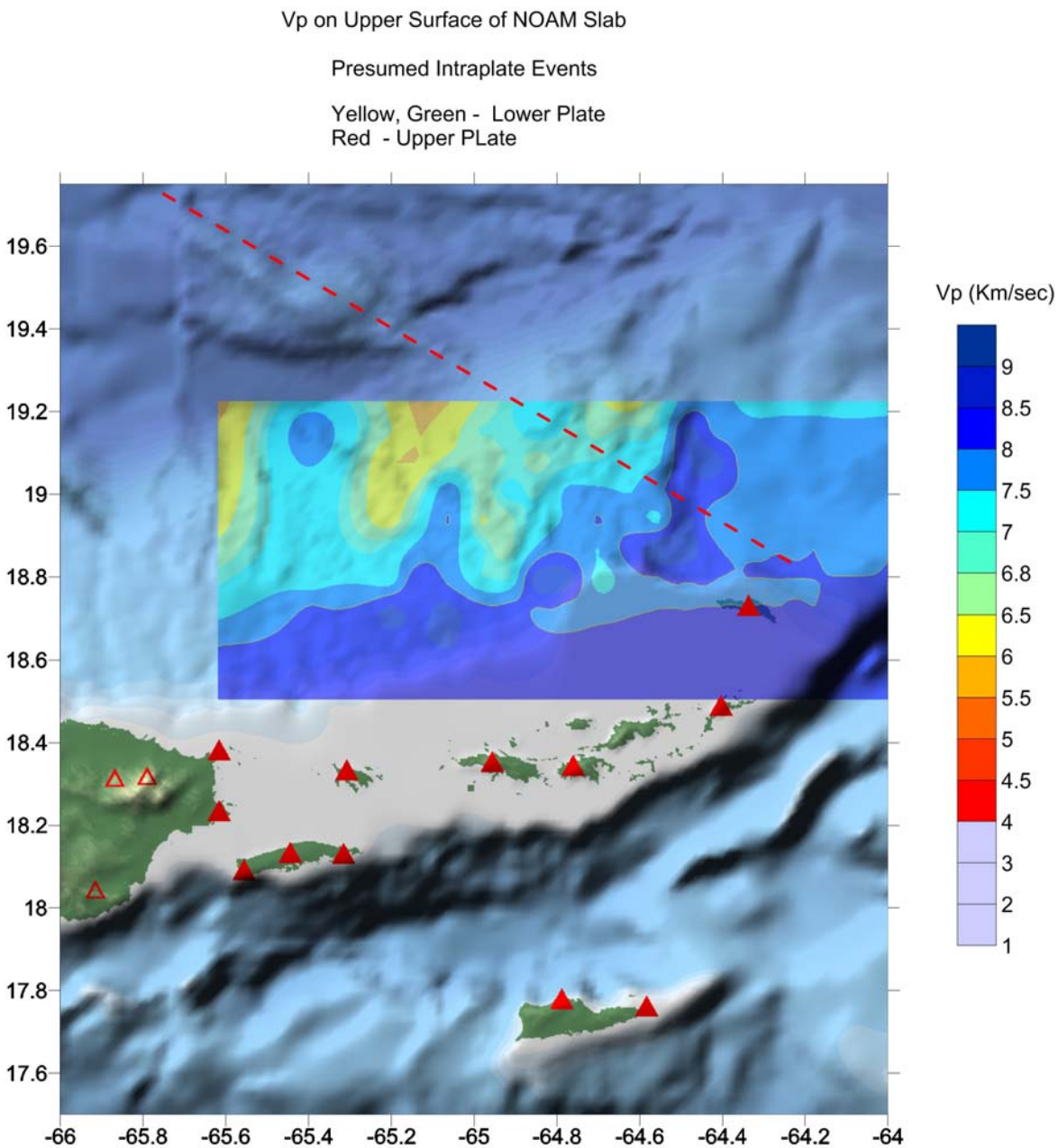

Figure 9. Estimated P-wave velocities for the crustal portion of the downgoing NOAM slab. Note that for much of the region velocities from 6.0-7.5 Km/sec, as expected for oceanic crust are observed. However, a large region with anomalously fast velocities is found east of about 64.6°W. While velocities in the region south of 18.7°N may not be well-resolved, the higher velocities observed there are consistent with the eclogitization of oceanic crust, and may indicate the lower limit of the seismogenic zone. Red dashed line is SE extension of Main Ridge on the subducted NOAM plate.

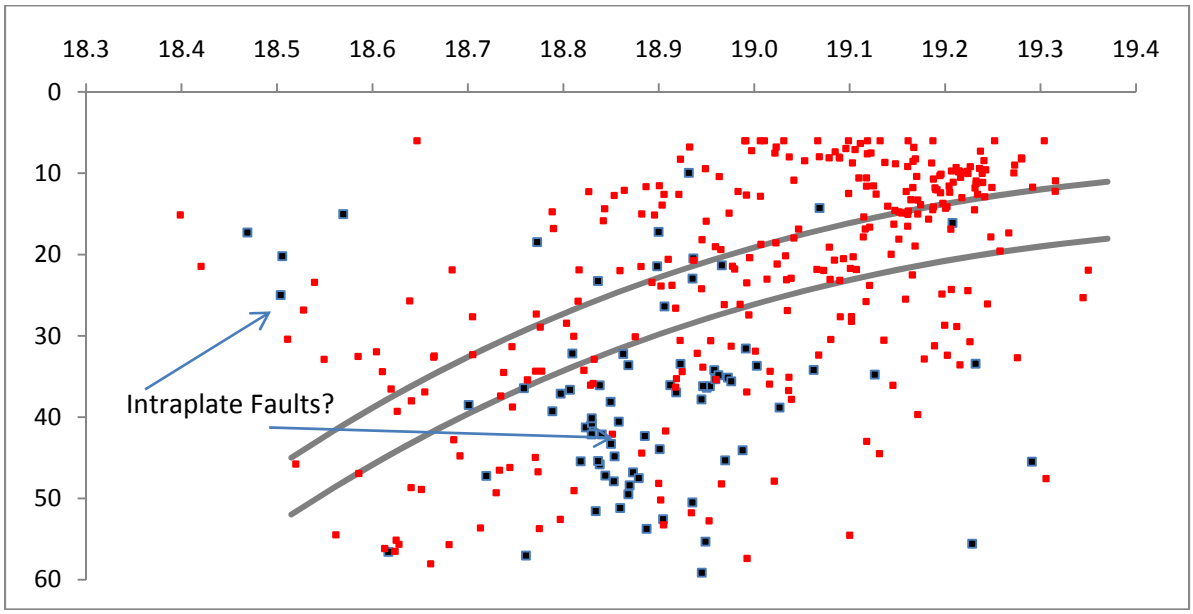

Figure 10. Vertical Cross section of well-recorded events (rms <0.25) along 150 Km of the subduction zone. Several groups of earthquakes do not fall on the main plate interface (grey curves). These intraplate events define steep-northerly dipping planes, and we suggest that they represent faulting within the downgoing and overriding plate. Blue symbols are events east of 64.5W. Most events in this region lie on an intraplate fault in the lower plate. Seismicity on the main plate interface is clearest between 19.2°N and 18.9°N.

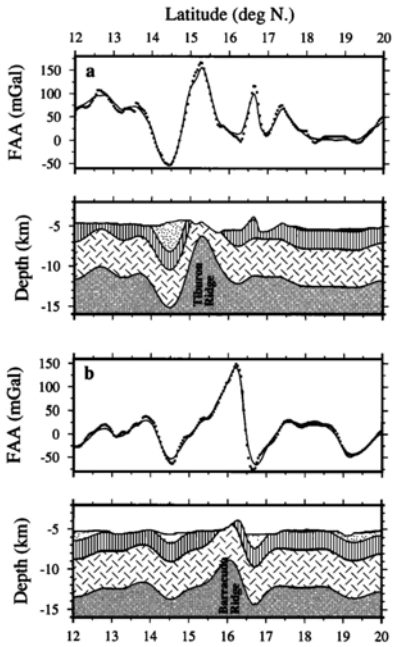

Fig. 15. Cross-sectional profiles from the multilayer model at the same locations as shown in Figure 12. Comparison with Figure 12 reveals that the elevated Moho topography underneath the Barracuda and Tiburon ridges, resulting from positive residual gravity anomalies, is quite similar in both models. However, the layer structure modeled from large negative residual gravity anomalies, as over sediment-filled troughs south of the Tiburon Ridge and on both sides of the Barracuda Ridge, is smoother than in the single-layer model, resulting in a more realistic Moho curvature.

Figure 11. From Muller and Smith (1993). Gravity-derived crustal models for the Tiburon and Barracuda ridges. These fracture-zone parallel ridges lay off the north Lesser Antilles. The NW extension of the Barracuda ridge in the Virgin Islands segment of the Caribbean subduction zone is represented by the Main Ridge. Muller and Smith (1993) conclude that these ridges, which were formed by relative motion between the North and South America Plates, have experience extension and compression, and that their structures are characterized by uplifted mantle and thinned crustal sections. In the case of the Tiburon Ridge the mantle is unusually shallow and the crust is as thin as 1.5 Km, with oceanic crustal layer 2 absent. We propose that the SE extension of the Main Ridge into the Virgin Islands segment of the subduction zone has a similar crustal structure and thus explains the mantle-like velocities observed (instead of oceanic crustal velocities) on the upper surface of the downgoing slab west of 64.6°W.

Conclusions

- The 1976 and 1979 marine experiments represents a valuable body of data for developing improved 3-D velocity models and earthquake location in the Puerto Rico Virgin Islands area.

- A 3-D P-wave velocity model for the Virgin Islands segment of the Puerto Rico subduction zone shows southerly dipping velocities layers consistent with subduction of North American Plate at the Puerto Rico trench.

- Layer thicknesses and velocities are consistent with normal oceanic crust west of 64.6°W. East of 64.6°W velocities are anomalously high reflecting mantle rather than crustal values. The near or total absence of oceanic crust velocities in the eastern portion of the study area can be explained by the presence of deformed oceanic crust on the downgoing plate.

- The anomalous Vp region on the downgoing plate lies along the extension of the Main Ridge, a feature similar in origin to the Tiburon and Barracuda ridge off the Lesser Antilles. Those ridges are character by uplifted mantle, and in the case of the Tiburon Ridge, nearly absent oceanic crust.

- Intraplate faults are identified near the main plate interface.

References

Asencio, E. 1980. Western Puerto Rico Seismicity. U.S. Department of the Interior, Geological Survey. Open-File Report 80-192.

Dillon, W. P., N. T. Edgar, K. M. Scanlon, and L. M. Parson, A review of the tectonic problems of the strike-slip northern boundary of the Caribbean plate and examination by GLORIA, in Geology of the United States Seafloor: The View from Gloria, edited by J. V. Gardner, M. E. Field, and D. C. Twichell, pp. 135 – 164, Cambridge Univ. Press, New York, 1994.

Ewing, M., Lonardi, A.G. and Ewing, J.I. 1965. The sediments and topography of the Puerto Rico Trench and outer ridge. Transactions of the 4th Caribbean Geological Conference, p.325-334.

Fischer, K. and W. McCann, 1984, Velocity Modeling and Earthquake Relocation in the Northeast Caribbean, Bull. Seism. Soc. Amer. 74(4), p1249-1262

Frankel, A., 1982b, Precursors to a magnitude 4.8 earthquake in the Virgin Islands: Spatial clustering of small earthquakes, anomalous focal mechanisms, and earthquake doublets, BSSA, vol 72,No4, 1277-1294.

Frankel, A., Mueller, C., Barnhard, T., Perkins, D., Leyendecker, E., Dickman, N., Hanson, S., and Hopper, M., 1996, National seismic hazard maps: documentation, *US Geol. Survey Open File Rpt. 96-532*, 110 p.

Frankel, Arthur (1982a): A Composite Focal Mechanism for Microearthquakes along the northeastern border of the Caribbean plate. Geophys. Res. Let. 9, 511-514.

Frankel, Arthur; Mccann, William R; Murphy, Andrew J (1980): Observations From a Seismic Network in the Virgin Islands Region: Tectonic Structures and Earthquake Swarms. JGR 85(B5), 2669-2678.

Grindlay, N., Mann, P., J. Dolan, and J-P Gestel, 2005, P. Mann ed., GSA Special Paper 385, Active tectonics & seismic hazards of PR, the virgin islands, and offshore areas, 31-61.

Jansma, P., Mattioli, G., 2005, GPS Results, from Puerto Rico and the Virgin Islands: Constraints on tectonics setting and rates of active faulting, in Mann ed., Active tectonics and seismic hazards of Puerto Rico, the virgin islands, and offshore areas: GSA special paper 385, p13-30.

LaForge, R., and W. McCann, 2005, A Seismic source model for Puerto Rico, for use in Probabilistic ground Motion Analyses, P. Mann ed., GSA Special Paper 385, Active tectonics & seismic hazards of PR, the virgin islands, and offshore areas, 223-248.

Mann, P., Calais, E., Ruegg, J.C., De Mets, C., Jansma, P.E., and Mattioli, G.S., 2002, Oblique collision in the northeastern Caribbean from GPS measurements and geological observations: Tectonics, v. 21, no. 6, p. 1057, doi: 10.1029/2001TC001304.

McCann, W. R., and L. R. Sykes, Subduction of aseismic ridges beneath the Caribbean plate: Implications for the tectonics and seismic potential of the northeastern Caribbean, J. Geophys. Res., 89, 4493 – 4519, 1984.

McCann, W., 2002, Microearthquake data elucidates details of Caribbean subduction zone: Seismological Research Letters, v. 73, p. 25–32.

McCann, W.R. 1985. On the earthquake hazards of Puerto Rico and the Virgin Islands. B.S.S.A., Vol.75,1:251-262.

Molnar, P., Sykes, L. R., 1969, Tectonics of the Caribbean and Middle America regions from focal mechanisms and seismicity, *Geol. Soc. America Bull.*, 80, 1639-1684.

Muller, R.D. & Smith, W.H.F. 1993. Deformation of the oceanic crust between the North American and South American plates. Journal of Geophysical Research 98: 8275–8291.

Murphy, A.J. and McCann, W.R. 1979. Preliminary results from a new seismic network in the North Eastern Caribbean. Bulletin of the Seismological Society of America, v.69, p.1497-1513.

Officer, C; Ewing,J; Hennion,J; Harkrider,D; Miller,D (1959): Geophysical investigations in the eastern Caribbean-summary of the 1955 and 1956 cruises. L. Ahrens et. al. Physics and Chemistry of the Earth, V.3: London, Pergamon Press,464 p.

Schell, B; Tarr,A (1978): Plate Tectonics of the northeastern Caribbean Sea region. Geologie en Mijnbouw 57, 319-324.

Sykes, L. R., and Ewing, M., 1965, The seismicity of the Caribbean region, *Jour. Geophys. Res.*, 70, 5065-5074.

Ten Brink, U., and 7 other authors, 2004, New Seafloor map of the Puerto Rico Trench helps assess earthquake and tsunami hazards, EOS, V85, #37, p349, 354.

Thurber C. and D. Eberhart-Philips ,1999, Local earthquake tomography with flexible gridding, Comput. Geosci., 25, 809-818.