FINAL REPORT

Constraints on active faulting and diffuse extension in Puerto Rico and the Virgin Islands from GPS geodesy

Grant award number: 04HQGR0091
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Element I
Keywords: GPS contiuous, GPS campaign, regional seismic hazard

NON-TECHNICAL SUMMARY

Data to assess active faulting in Puerto Rico and the Virgin Islands were obtained using Global Positioning System (GPS) geodesy. Analysis of the GPS data is consistent with EW-oriented extension across the island of Puerto Rico. Extension is greater in the west than east. The loci of deformation are not known, but preliminary results indicate that the active structures are likely west of the San Juan metropolitan area. EW-extension that may be accommodated along subaerial faults in Puerto Rico has not previously been recognized and thus not considered in seismic hazard analysis of the island.

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SUMMARY

This final report is submitted in keeping with the requirements as described in the award. The start date of this 2-year project was March 1, 2004.

Data to assess active faulting and diffuse extension in Puerto Rico and the Virgin Islands (PRVI) were obtained using Global Positioning System (GPS) geodesy, building on earlier work conducted in PRVI and also funded by NEHRP. Analysis of the GPS data is consistent with westward-increasing EW-extension across PRVI, including EW-extension of a few mm/yr across the island of Puerto Rico. The loci of deformation are not known, but preliminary results indicate that the structures are likely west of the San Juan metropolitan area. EW-extension that may be accommodated along subaerial faults in Puerto Rico was not previously considered in seismic hazard analysis of the island.

INVESTIGATIONS UNDERTAKEN

Overview and background: Puerto Rico and the northern Virgin Islands occupy a ~ 200 km wide and ~ 400 km long shallow bathymetric platform at the eastern end of the Greater Antilles in the deformation zone of the North American-Caribbean plate boundary (Figure 1a). Motion of the Caribbean with respect to North America is 19.4 ± 1.2 mm/yr toward N79°E ± 3° (1s), making convergence highly oblique to the east-west trending boundary zone (Jansma et al., 2000; Jansma and Mattioli, 2005). The features that define the edges of the Puerto Rico and northern Virgin Islands platform are the Puerto Rico trench and Muertos trough to the north and south, respectively, the Mona passage to the west and the Anegada passage to the southeast (Figures 1a and 1b).

The northeastern Caribbean experiences hundreds of earthquakes per year, the majority of which are small and located offshore (Figure 1). Several large events (M > 6.0) have occurred since the early 1900's, including the 1915, 1920, and 1943 earthquakes north of the Mona passage and likely along the North American plate interface (Mw=6.7, 6.5, and 7.8 respectively), the 1917 event in the subducting North

American slab (Mw=6.9), the 1918 Mona passage earthquake at ~ 20 km depth (Mw=7.2), and the 1916 (Mw=6.8) and 1946 earthquakes near Hispaniola (Doser et al., 2005). Three moderate events are known for the Virgin Islands over the same time period: 1930 (Mw=6.0) in the North American plate and 1919 (Mw=6.2) and 1927 (Mw=5.6) along the plate interface (Doser et al., 2005). Other earlier events are the 1867 Anegada earthquake (Ms=7.3), the 1787 Puerto Rico trench earthquake (M=7.5?) and the 1670 San German earthquake (M=6.5?) (Pacheco and Sykes, 1992). Noting the concentration of events along the structures that bound the shallow platform and the paucity of on-land events, workers proposed a rigid, Puerto Rico-northern Islands block (PRVI) within the Caribbean-North American boundary zone (Figure 1) (Byrne et al., 1985; Masson and Scanlon, 1991).

GPS geodetic results confirm the existence of an independent PRVI (Jansma and Mattioli, 2005). The GPS data also suggest that westward-increasing EW-extension occurs across Puerto Rico and the northern Virgin Islands from zero in the east at Virgin Gorda to 5±2 mm/yr across the Mona Canyon between Hispaniola and western Puerto Rico. EW-extension of 3±1 mm/yr may be accommodated across the island of Puerto Rico. The loci of deformation are not known. Preliminary results indicate that the structures may be west of the San Juan metropolitan area, but additional time on existing sites is necessary to define this and other remaining uncertainties better. EW-extension across PRVI that may be accommodated along subaerial faults in Puerto Rico has not previously been considered in seismic hazard analysis of the island. Past attention has been centered on the Lajas Valley in the southwestern part of the island where seismicity levels are the highest in PRVI (Figure 2).

Most early studies of on-land faults in Puerto Rico focused primarily on the Great Northern and Great Southern Puerto Rico fault zones and associated structures, which are major left-lateral strike-slip systems that cut Miocene and older rocks (Glover, 1971; Erickson et al., 1990) (Figure 2). Both faults are covered by little deformed Neogene sediments. Whether they represent inherited zones of weakness that may localize deformation is not well known. McCann (1985) considered the Great Northern fault zone to be largely quiescent despite the occurrence of small earthquakes along the structure. Preliminary GPS geodetic results did permit a small amount of displacement (< 2 mm/yr) across the Great Northern Puerto Rico fault zone (Jansma and Mattioli, 2005), but more recent results suggest that no slip occurs (Jansma et al., in prep.)

In contrast, the southern end of the Great Southern Puerto Rico fault zone immediately offshore disturbs Recent shelf sediments (Mann et al., 2005b). Left-lateral strike-slip faults that disrupt Holocene reflectors were identified along the projected offshore trend of the fault zone, suggesting that the kinematics of the immediate offshore region of south-central Puerto Rico are dominated by sinistral transtension (Mann et al., 2005b). The projection of the northern end of the Great Southern Puerto Rico fault zone, which continues offshore into Mona Canyon, is sub-parallel to faults of similar orientation (NW/SE), which are seismically active (McCann, 1985; Joyce et al., 1987). In addition, an EW-striking splay of the Great Southern Puerto Rico fault zone at its northern end, the Cerro Goden fault, cuts across to the west coast of Puerto Rico about 10 km north of the city of Mayagüez (Figure 2). Mann et al. (2005a) infer late Quaternary oblique faulting with components of normal motion and right-lateral strike-slip on the basis of offset stream drainages and terraces along the western end of the fault. The offshore extension of the Cerro Goden is imaged in marine seismic profiles and continues to the southern limit of the Mona rift (Grindlay et al., 2005). In contrast, GPS geodetic results permit only minimal on-going displacement along the Cerro Goden fault. Changes in baseline length between two continuous GPS receivers on either side of the fault are less than 1 mm/yr over a period greater than 7 years (Jansma and Mattioli, 2005; Jansma unpublished data).

Documentation of features in the near shore or on-land that offset Quaternary units was limited (e.g. McCann, 1985; Meltzer and Almy, 2000), leaving most workers to model Puerto Rico as a rigid block (e.g. Byrne et al., 1985; Masson and Scanlon, 1991). Shallow microseismicity does occur onshore, but the historic record is consistent with major events limited to the offshore region (McCann, 2002). The recognition of Quaternary displacements, coupled with observations of shallow seismicity in western Puerto Rico, however, argues against rigid-block behavior. In addition, the complexity of faulting identified in the nearshore of western Puerto Rico (Grindlay et al., 2005) and on-land in the Lajas Valley (Prentice and Mann, 2005) point to a potentially diffuse western boundary of PRVI south of the Mona rift.

The highest levels of onshore seismicity are in the Lajas Valley (Asencio, 1980; McCann, 2002), an EW-trending feature in southwestern Puerto Rico along whose southern boundary, the South Lajas fault, has been mapped and trenched (Meltzer and Almy, 2000; Prentice and Mann, 2005) (Figure 2). The last rupture occurred within the previous 5,000 years, but no minimum age could be established (Prentice and Mann, 2005). Lack of detailed exposure precluded estimation of the magnitudes of potential earthquakes along the South Lajas fault, but Prentice and Mann (2005) note that faults that rupture to the surface are routinely capable of generating M > 6 and may produce M > 7 events. In addition, Tuttle et al. (2005) document abundant liquefaction features in western Puerto Rico that they attribute to three events with M > 6 within the last 500 years. One of the events likely was the 1918 Mona rift event, but the other two have epicenters, which are not well constrained. A high-resolution seismic survey failed to image an extension of the fault offshore (Grindlay et al., 2005), but this does not preclude recent displacement. Factors that may contribute to masking of the feature offshore include recent sedimentation, lack of sufficient resolution of the seismic instrumentation, or potential strike-slip displacement, which is difficult to image. Indeed, Quaternary transtension along the southern edge of the Lajas Valley was interpreted from seismic reflection profiles (Meltzer, 1997; Almy et al., 2000) and confirmed by trenching of the South Lajas fault (Prentice and Mann, 2005). The sense of strike-slip motion, however, could not be established. In contrast, results from GPS geodesy are most consistent with sinistral transpression across the South Lajas fault (Jansma and Mattioli, 2005).

Because the GPS-derived residual velocities of individual sites in PRVI are small (on the order of a few mm/yr) and the Caribbean reference frame is poorly constrained, errors remain large and limit estimation of discrete fault slip rates. In addition, many of the PRVI sites had short (< 4 year) time series. One of the goals of this project was to reduce the errors significantly by the additional two-years of data that were collected during the tenure of this award.

GPS network in PRVI

GPS measurements were first collected in the northeastern Caribbean in 1986 at six locations and were re-occupied in 1994 (Dixon et al., 1998). The network was densified during CANAPE and each subsequent year. Measurements have been made on subsets of the network every year since 1994 .

The GPS network in Puerto Rico and the Virgin Islands (Figure 2) consists of the original 1994 CANAPE locations (ISAB, PARG, and GORD) plus campaign sites MIRA (Miradero-Mayagüez), ZSUA and ZSUB (San Juan), MAZC (Mayagüez airport), CIDE (UPRM), MONA (Mona island), DSCH (Desecheo island), ADJU (Adjuntas), ARC1 and ARC2 (Arecibo), CCM5 (Ponce), VEGA (Vega Alta), CAJA, (Caja de Muertos Island), FAJA (Fajardo), LAJ1, LAJ2, and LAJ3 (Lajas Valley), SALN (Salinas), VIEQ (Vieques), ANEG (Anegada, British Virgin Islands), BEEF (Tortola, British Virgin Islands), BREW (Tortola, British Virgin Islands) and other sites for which only one epoch of measurements exists. The continuous sites are GEOL in Mayagüez, FAJA in Fajardo, UPRR in Rio Piedras, and UPRH in Humacao operated by the Department of Geosciences, University of Arkansas, and ZSU1 in San Juan and PUR3 in Aguadilla maintained by the U.S. Coast Guard. FAJA, UPRR and UPRH were established in 2000 as part of an earlier NEHRP award. Details of campaign observations from 1994 to 2002 can be found in Jansma et al. (2000) and Jansma and Mattioli (2005).

All of the sites in Puerto Rico and its islands (Mona, Desecheo, Vieques, Caja de Muertos) were re-occupied during 2005 and 2006 as part of this project. Occupations consist of a minimum of 8 hours of data collection each day for 3 days. Sites in Puerto Rico were re-occupied by Mr. Andy Eaby who served under contract to us as part of this project. Sites in the British Virgin Islands were re-occupied by graduate student Henry Turner of the University of Arkansas and NSF-REU (Research Experiences for Undergraduates) students Sarah Stamps of the University of Memphis and Adrian Baldwin of the University of Arkansas, Pine Bluff in 2005 and recently re-occupied by students from the University of Arkansas. One problem that we diagnosed after 2005 was a faulty receiver/antenna combination that gave us erroneous measurements. For this reason, some of the sites do not have the requisite number of epochs to generate robust velocities although they were occupied three times. We are in the process of correcting for the error, re-processing the data, and collecting additional occupations on critical sites.

GPS data processing

All data are currently processed as free-network point positions using GIPSY-OASISII (v. 2.6.4) (Lichten, 1990; Zumberge et al., 1997). Free-network solutions are transformed, scaled, and rotated into ITRF05 (the current realization of the International Terrestrial Reference Frame, epoch 2005) using x-files from the Jet Propulsion Laboratory (Blewitt et al., 1992; Heflin et al. 1992). Because ITRF-05 has just been released, reprocessing of all previously acquired data from ITRF00 to the new reference frame is on-going. All processing uses final, precise non-fiducial orbit, earth-orientation, and GPS clock files from JPL (300 s epoch). Time series velocity errors are calculated using the formulation of Mao et al. (1999), which includes both colored (time-correlated) and white noise contributions and an assumed estimate of 1 mm/$\sqrt{\text{yr}}$ of random walk noise at each site. Component site velocities are calculated in ITRF00 or ITRF05 using post-processing software modules, which allow estimation of component offsets along with estimates of velocities in a rapid and internally consistent way that includes the full-covariance of each daily site position in the analysis. Final velocities and errors in the Caribbean reference frame are calculated using the current best-fit model for Caribbean motion with respect to the ITRF00 or ITRF05. Caribbean fixed velocities include the full covariance of the individual sites velocities and the predicted motion of the Caribbean plate at that location (DeMets et al., 2007). We also included analysis modules that allowed for estimation of tropospheric gradients and rigorous calculation of ocean loading effects and incorporated qualitative estimates of correlated site motion for all sites in the northeastern Caribbean.

Quantitative modeling

We have developed kinematic-coupling models to examine elastic strain accumulation and co-seismic displacements in the northeastern Caribbean (Manaker et al., 2006; in review). Our initial efforts use simple 2D elastic models based on the formulation of Savage (1982). While these simple models allow one to explore the control of slab dip angle, degree of kinematic coupling, and locking depth, they are not adequate to address the complex geometry and kinematics of the PRVI subduction zone. We have now developed 3D elastic dislocation models for the geometry and plate kinematics of the PRVI, Lesser Antilles, and Middle America subduction zones. This was done using the Department of Energy code DISL (Larsen, 1998), which is based on the formulations of Chinnery (1961), Savage and Hastie (1966), and Mansinha et al. (1971). This code allows one to include a more realistic geometry of a curved subduction interface, by calculating the displacement on a series of linked fault patches. It retains the constraint of determining the displacements for an elastic half-space, however.

Results

The current GPS-derived velocity field is shown in Figure 3. Our reprocessing experiments, which include the effect of ocean loading at a limited number of CGPS sites (including PUR3, GEOL, FAJA, and HUMA), demonstrate that there is significant improvement in the precision of the site positions, lowering our noise estimates on the calculated velocities. The effect is most pronounced in the east and vertical components, with an improvement of 4.3% and 21.6%, respectively. Common mode corrections, which are weighted by the inverse square of radial distance from our regional and other far-field CGPS sites, also lowers noise estimates substantially on the campaign sites. Velocities at BEEF, BREW and VIEQ, for which only two epochs are available, are significantly different from those elsewhere in the northern Virgin Islands and eastern Puerto Rico. The faulty antenna/receiver combination was used at these sites. The velocity at ANEG seems more reasonable, but is faster than that expected given the velocity at GORD. Additional data collection is necessary as is further data processing to correct for the bias that the faulty antenna/receiver pair introduces.

Analysis of GPS data is consistent with a distinct PRVI microplate at the > 99% confidence level that translates westward at 2.6±2.0 mm/yr relative to the Caribbean and moves eastward at 15.6±2.7 mm/yr relative to North America (Jansma et al., 2000; Jansma and Mattioli, 2005). Most slip, therefore, is localized offshore northern Puerto Rico, but some slip must occur on the island and offshore to the south. Simple elastic models show that locking along offshore faults to the north and/or the plate interface alone cannot account for the GPS velocity field (Calais et al., 2002).

The GPS data also suggest that westward-increasing EW-extension occurs across PRVI from near zero in the east at Virgin Gorda to 5 mm/yr across the Mona Canyon between Hispaniola and Puerto Rico. EW-extension of 2-4 mm/yr is accommodated across the island of Puerto Rico. The loci of deformation are not known. Preliminary GPS data suggest that the active structures may be west of the San Juan metropolitan area, but additional time on existing sites is necessary to define this better. EW-extension across PRVI that may be accommodated along subaerial faults in Puerto Rico has not previously been considered in seismic hazard analysis of the island. Assessing block rigidity and displacement along on-land faults in PRVI were the main foci of this USGS-NEHRP award. Although we have made progress, such as eliminating the Great Northern Puerto Rico Fault Zone as the locus of deformation, the slow deformation rates have made discriminating between diffuse extension over a broad area of western Puerto Rico or localized extension along other discrete faults difficult. Obtaining additional measurements to lengthen the time series will greatly improve our ability to distinguish between the two end-members.

Another focus was the Lajas Valley in southwestern Puerto Rico. Despite recognition decades ago of the potential for earthquakes in the Lajas Valley (Asencio, 1980), the GPS geodetic data there were limited. Our GPS geodetic results are consistent with ≤ 2mm/yr of likely right-lateral transpression across the Lajas Valley, which is in agreement with slip estimates from composite focal mechanisms (Doser et al., 2005), but is inconsistent with paleoseismological data derived from trenching (Prentice and Mann, 2005). The errors associated with the GPS measurements of the Lajas Valley deformation remain large because time series are short.

The final result, which was unexpected, concerns the location and kinematics of the southeastern boundary of PRVI. Three possibilities exist: 1) a transtensional boundary in the Anegada passage that accommodates a few mm/yr of motion between PRVI and the northeastern Lesser Antilles (Jansma et al., 2000; Jansma and Mattioli, 2005); 2) a strike-slip boundary south of Guadeloupe that defines the southern boundary of a block that contains both PRVI and the northeastern Lesser Antilles and moves with the Caribbean plate—in this model internal deformation of PRVI and displacement along the Anegada passage are negligible (Calais et al., 2002); and 3) a transpressional boundary between eastern PRVI and a distinct Lesser Antilles forearc sliver that translates toward the NNW relative to the Caribbean at 5-7 mm/yr (Figure 4) (Lopez et al., 2006). Our preliminary data are most consistent with alternative 1.

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ABSTRACTS

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a)

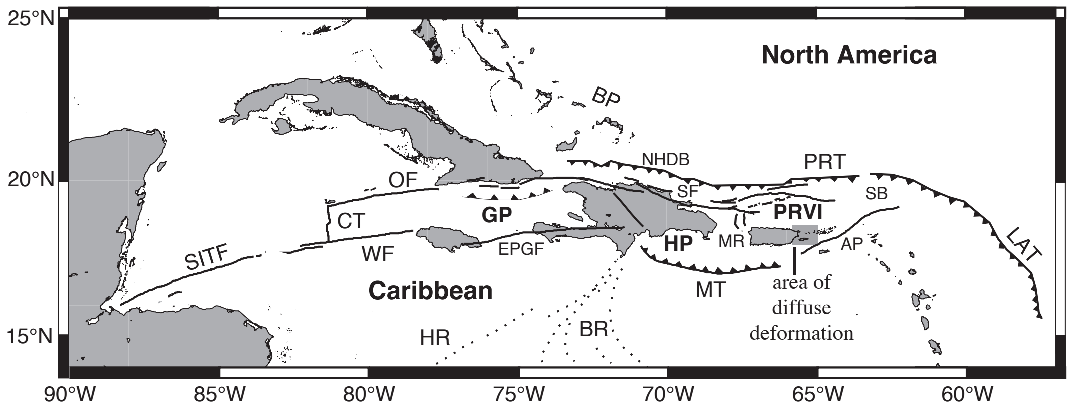


Figure 1: a) Map of northern Caribbean plate boundary showing microplates and structures. AP: Anegada Passage. BP: Bahamas Platform. BR: Beata Ridge. CT: Cayman Trough Spreading Center. EPGF: Enriquillo-Plantain Garden Fault. GP: Gonvave Platelet. HP: Hispaniola Platelet. HR: Hess Rise. LAT: Lesser Antilles Trench. MR: Mona Rift. MT: Muertos Trough. PRVI: Puerto Rico-Virgin Islands block. SB: Sombrero Basin. SITF: Swan Islands Transform Fault. SF: Septentrional Fault. WF: Walton Fault.

b)

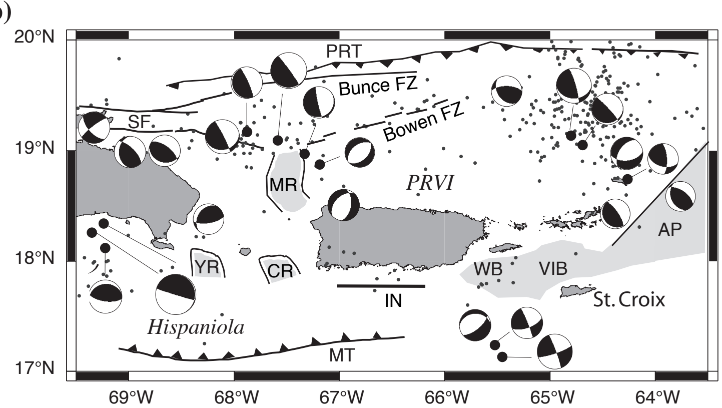
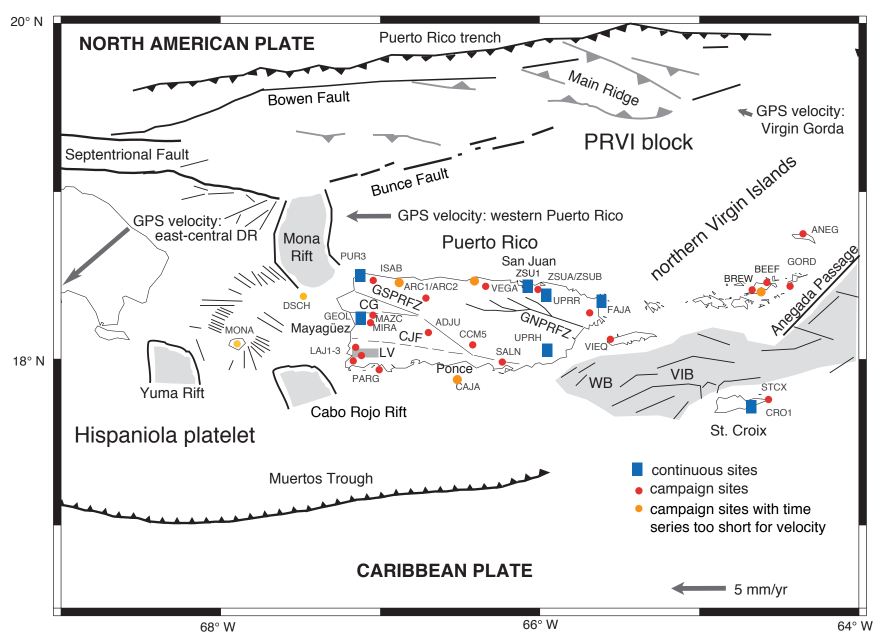


Figure 1: b) Focal mechanisms for depth < 35 km for eastern Hispaniola, Puerto Rico and Virgin Islands. Sources are the Harvard CMT catalogue, the Puerto Rico Sesimic Network, Deng and Sykes (1995), and Molnar and Sykes (1969). Dots are USGS epicenters (see Figure 1a above). Abbreviations as in Figure 1b. VIB: Virgin Islands Basin. WB: Whiting Basin. YR: Yuma Rift. CR: Cabo Rojo rift. IN: Investigator fault.

Figure 2: Current mixed-mode GPS geodetic network in the northeastern Caribbean. GNPRFZ: Great Northern Puerto Rico Fault Zone. GSPRFZ: Great Southern Puerto Rico Fault Zone. CG: Cerro Goden Fault. CF: Cordillera Fault. LV: Lajas Valley (medium gray shaded rectangle in southwestern Puerto Rico). Major offshore structures also are shown. Light gray shaded regions are zones of inferred extension. WB: Whiting Basin. VIB: Virgin Islands Basin. Arrow in Dominican Repubic is GPS-derived velcoity relative to fixed Caribbean for central Hispaniola, south of the Septentrional fault. Arrow north of the island of Puerto Rico is average GPS-derived velocity relative to the Caribbean for PRVI. Arrow in the notherhern Virgin Islands is GPS-derived velocity relative to the Caribbean for site in Virgin Gorda. Length of arrow in lower left corresponds to 5 mm/yr for scale. Error ellipses are not shown for clarity.



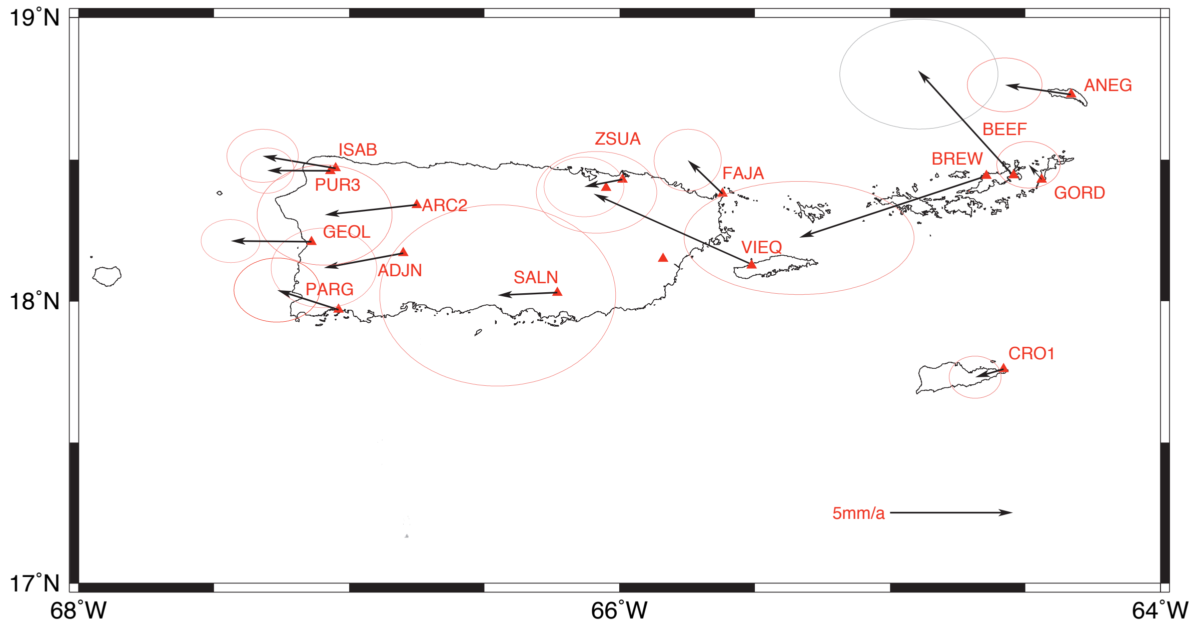


Figure 3: GPS-derived site velocities for PRVI from data acquired through 2006. Note large velocities for BREW and BEEF relative to GORD and ANEG. Additional measurements are required to determine the cause of this discrepancy. Velocities are relative to fixed Caribbean. Error ellipses are 95% confidence.

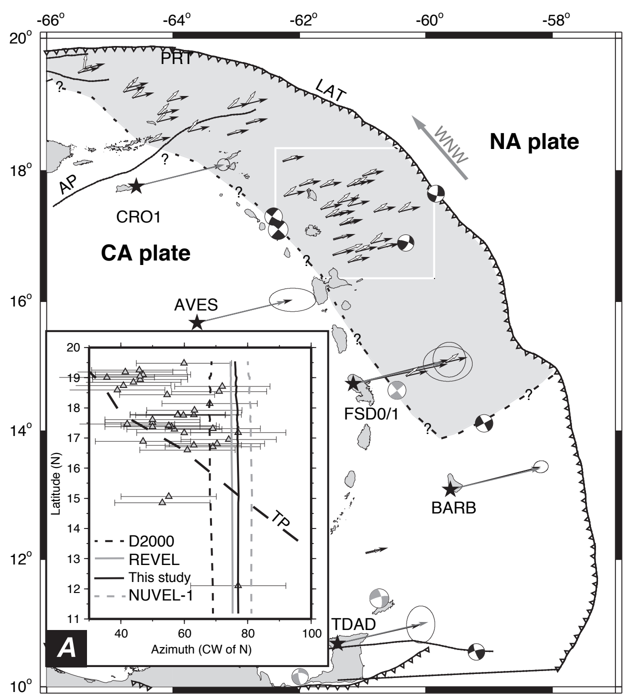


Figure 4: Map from Lopez et al. (2006), showing postulated forearc sliver of the northern Lesser Antilles that translates to the NW/WNW relative to the Caribbean plate. Determination of forearc sliver motion was from earthquake slip vectors. Note the problematic location of the northern boundary of the purported forearc. White arrows are deviations of slip vectors from predicted Caribbean-North American plate motion from a 9 site model for the stable Caribbean. Modified from Lopez et al. (2006).