FINAL REPORT

Assessing Seismic Hazard in Puerto Rico and the Virgin Islands Using the Historical Earthquake Record and Mixed-Mode GPS Geodesy: Collaborative Research Between the University of Puerto Rico, Mayagüez and the University of Texas at El Paso

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Summary

This project report is submitted in keeping with the requirements as described in the award. The original grant was awarded to the University of Puerto Rico, Mayagüez, but subsequently was transferred to the University of Arkansas due to the relocation of the PI's from Puerto Rico to Arkansas. A start date of January 1, 2001 and a completion date of December 31, 2002 were assigned to the project at the University of Arkansas.

Data to assess seismic hazard in Puerto Rico and the Virgin Islands were obtained using Global Positioning System (GPS) geodesy. Measurements were collected at 21 campaign and 6 continuous sites. Emphasis is on quantifying surface displacement of active faults. Preliminary results derived from data from a subset of the existing GPS network are consistent with deformation on the island of Puerto Rico limited to less than a few mm/yr, including areas where active faults are proposed. Most of the active faulting occurs offshore north of the island of Puerto Rico, where displacements of 16 mm/yr must be accommodated. More recent results are consistent with westward increasing EW-oriented extension from the Virgin Islands across Puerto Rico and into eastern Hispaniola. East-west extension of 2 to 3 mm/yr is observed across the island of Puerto Rico, consistent with composite focal mechanisms and regional epicentral distributions. Although the loci of extension are not known, similarity of GPS-derived velocities among sites in eastern Puerto Rico suggest the active structures lie west of the San Juan metropolitan area. Reactivation of the Great Northern and Southern Puerto Rico fault zones as oblique normal faults with right-lateral slip is a possibility. East-west extension of up to 2 mm/yr also must exist between eastern Puerto Rico and Virgin Gorda. These extensional belts allow eastward transfer of slip between North America and the Caribbean from the southern part of the plate boundary zone in the west to the northern segment in the east.

Overview and background

Puerto Rico and the Virgin Islands (PRVI) have a long historical record (~400 years) of damaging earthquakes, including the 1916, 1918, and 1943 Mona Passage earthquakes (Ms=7.2, 7.3, and 7.5 respectively), the 1867 Anegada Passage 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). Current seismicity mimics the pattern of the large, historic events. Earthquakes are concentrated offshore Puerto Rico in the Mona and Anegada Passages, the Muertos Trough, and the Puerto Rico trench. The highest levels of onshore seismicity are in southwest Puerto Rico in the Lajas Valley, an EW-trending feature, which continues west offshore and passes south of the southern termination of the Mona Canyon (Figures 1 and 2).

During the last two decades, significant progress has been made toward assessing the seismic hazard of PRVI. This includes the establishment and continued enhancement of the Puerto Rico Seismic Network, the development of regional tectonic models, the recognition of microplate behavior in the northeastern Caribbean, the documentation of potentially active faults onshore and offshore, and the assessment of relative motion between the Caribbean and North America plates. Despite advances in the state of knowledge, however, key aspects of the fundamental geologic and geophysical underpinnings necessary to delineate seismic source zones for evaluation of seismic risk remain either largely unconstrained or controversial. These are summarized in three points.

- *What is the nature of deformation in the plate boundary zone near PRVI, i.e. does the zone contain distinct rigid blocks which move separately from one another or are displacements taken up continuously across its width in simple shear?*

- *Where are the active faults?*
- *What is the mechanical behavior of mapped and potentially active faults, i.e. are the faults locked and accumulating strain that must be released catastrophically during a significant earthquake or are the faults creeping aseismically?*

These questions must be answered to evaluate seismic risk quantitatively and to plan appropriately for development of civil infrastructure. The only published earthquake hazard map for Puerto Rico (McCann, 1994), for example, does not include calculation of the risk of rupture of specific faults because reliable data on deformation rates across seismogenic structures were not available. A 1999 draft USGS hazard map, which used the sparse GPS-velocity field in Dixon et al. (1998) to partition slip among various areal zones roughly coincident with mapped onshore and offshore features, yields probability for damaging ground motion in western Puerto Rico equivalent to that for Seattle, Washington.

Better definition of the possible seismogenic features within the northeastern Caribbean and their potential associated slip is essential to assessing earthquake hazard and establishing appropriate actions to mitigate seismic risk. One of the most powerful techniques to provide such data is Global Positioning System (GPS) geodesy, which can obtain positions of points on Earth's surface to a precision of a few millimeters. Changes in positions over time allow scientists to pinpoint locations of active faults, document their associated displacement and mechanical behavior, and model the deformation field to improve understanding of the potential for destructive earthquakes. GPS arrays now are an integral part of earthquake monitoring networks worldwide.

This project emphasizes the collection and analysis of surface deformation data obtained from mixed-mode Global Positioning System (GPS) geodetic studies, on-going in PRVI since

1994, to determine slip rates and strain accumulation along active structures in PRVI. The project is part of a collaborative study with the University of Texas at El Paso (UTEP) of historic earthquakes of M>6.0 occurring from 1906 to 1960 to identify possible seismogenic structures and to estimate how much of the deformation has been released seismically over the past 80 to 90 years. The existing PRVI mixed-mode GPS array consists of 4 continuous GPS sites and 21 campaign sites. Three continuous sites and 11 campaign sites were added as part of our USGS-NEHRP work. In addition, 2 continuous GPS (CGPS) sites exist within the region (PUR3 and CRO1), which we do not maintain but for which we process data.

Tectonic setting

Puerto Rico and the northern Virgin Islands define the eastern terminus of the Greater Antilles, which extend eastward from offshore eastern Central America to the Lesser Antilles volcanic arc and mark the boundary between the Caribbean and North American plates. Tectonic models for the northern Caribbean (e.g., Byrne et al., 1985; Mann et al., 1995) propose active microplates within the boundary zone on the basis of geologic and earthquake evidence. Seismicity along the east-west trending boundary between the North American and Caribbean plates is consistent with evolution of the boundary zone from a relatively simple set of transform faults in the west to a more complex deformation zone approximately 250 km wide in the east (Figure 1). Motion along the predominantly east-west striking major structures of the northern Caribbean is primarily left-lateral. In the west, the Swan and Oriente transform faults define the EW-trending Cayman trough and bound the short (~100 km), NS-trending Mid-Cayman spreading center (Figure 1a). In Hispaniola, Puerto Rico and the Virgin Islands, the northern and southern limits of the plate boundary zone are defined by the Puerto Rico trench and the Muertos trough, respectively. Three microplates lie within this diffuse boundary zone (Figure 1a): 1) the Gonave in the west (Mann et al., 1995); 2) the Hispaniola in the center (Byrne et al., 1985); and 3) the Puerto Rico-northern Virgin Islands (PRVI) in the east (Masson and Scanlon, 1991). Such a microplate model assumes that nearly all of the deformation associated with North America-Caribbean motion is concentrated along the faults that bound the three rigid blocks: the Oriente, Septentrional, Enriquillo-Plantain Garden, and Anegada faults, the Muertos trough and North Hispaniola deformed belt, and the Mona rift faults northwest of Puerto Rico (Figures 1 and 2).

Recent results from GPS geodesy support the presence of an independently translating Puerto Rico-northern Virgin Islands (PRVI) microplate within the northeastern Caribbean (Jansma et al., 2000) with ~85% of the relative motion occurring between PRVI and North America. The geodetic data are not consistent with models that advocate either counter-clockwise rotation of PRVI about a nearby vertical axis (Masson and Scanlon, 1991; Reid et al., 1991) or eastward tectonic escape of the block within the Caribbean-North American plate boundary zone (Jany et al., 1987). Because velocities of PRVI with respect to the Caribbean plate are small and the errors were significant, both as a consequence of the paucity of data for a Caribbean reference frame and the geographically-restricted GPS network, Jansma et al. (2000) were limited in their interpretation of interplate deformation along the PRVI-Caribbean boundary and intrablock deformation of PRVI. The primary objective of this project was to refine the analysis and interpretation of Jansma et al. (2000) through the acquisition of longer time series on existing sites and the collection of additional data from new continuous and campaign GPS sites.

On-land faulting

Most studies of on-land faults in Puerto Rico have focused primarily on structures that cut Tertiary and older rocks (Glover and Mattson, 1960; Glover, 1971; Erickson et al., 1990; 1991). Prior to the work of Prentice et al. (in press), documentation of features that offset Quaternary units has been limited (e.g. McCann, 1985; Meltzer et al., 1995), leaving most workers to model Puerto Rico as a rigid block (e.g. Masson and Scanlon, 1991). Shallow microseismicity does occur onshore, but the historic record is consistent with major events limited to the offshore region (McCann and Pennington, 1990). The recognition of Quaternary displacements when coupled with observations of shallow seismicity in western Puerto Rico, however, appears to argue against rigid-block behavior. The question arises as to how rigid is "rigid PRVI"? Do faults exist within PRVI, particularly onshore, that are capable of producing significant and locally damaging earthquakes? Do displacement rates along mapped faults agree with those derived from the geologic data?

The highest levels of onshore seismicity are in the Lajas Valley (Asencio, 1980), an EW-trending feature in southwestern Puerto Rico, which continues offshore to the west and passes south of the southern termination of the Mona Canyon, where offshore faults are mapped (Figure 2). Quaternary offsets along the southern edge of the Lajas Valley were interpreted from seismic reflection profiles (Meltzer et al., 1995; Meltzer, 1997) and active faulting was inferred from the "basin-and-range" style topography of the region (Joyce et al., 1987). Displacements along the east-west striking faults are inferred to be normal with components of strike-slip (Meltzer, 1997; Almy et al., 2000; Prentice et al., 2000).

In addition, the island of Puerto Rico is traversed by two northwest-southeast striking fault zones: 1) the Great Northern Puerto Rico fault zone (GNPRFZ) and 2) the Great Southern Puerto

Rico fault zone (GSPRFZ) (Figure 2). The fault zones were active during the Eocene and record predominantly thrust and left-lateral displacement in response to amalgamation of discrete island arc terranes at the leading edge of the Caribbean plate into PRVI (Glover and Mattson, 1960; Glover, 1971; Erickson et al., 1990; 1991). Both the GNPRFZ and the southern end of the GSPRFZ are covered by little deformed Neogene strata. The two fault zones, however, represent large areas of weakness within Puerto Rico along which active displacements may be localized. Indeed, the southern end of the GSPRFZ immediately offshore may cut and disturb Recent shelf sediments (McCann, 1985; Joyce, pers. comm.). The projection of the northern end of the GSPRFZ, 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 GSPRFZ, the Cerro Goden fault, cuts across to the west coast of Puerto Rico about 10 kilometers north of the city of Mayagüez (Figure 2). Whether Quaternary motion occurred along the Cerro-Goden fault is unknown, although the offshore projection of the fault merges with other mapped structures that presumably are Quaternary in age. Lao-Davila et al. (2000) infer Recent displacement with components of normal motion and left-lateral strike-slip on the basis of offset stream drainages and terraces. Some workers have identified the surficial expressions of the Cordillera and Joyuda faults, which they argue may correspond to a WNW/ESE trend across southwestern Puerto Rico that is defined by a series of epicenters of small earthquakes that were recorded by the Puerto Rico Seismic Network in 1995 (Moya, personal communication). Geological estimates for displacements along the fault are unconstrained.

Prior GPS results for Puerto Rico and the northern Virgin Islands

Jansma et al. (2000) provided a detailed discussion and interpretation of GPS geodetic data collected in PRVI from 1994 until 1999. With the exception of two sites (ZSUA in San Juan and GORD in Virgin Gorda), the network consisted of stations in western Puerto Rico. Their results, therefore, emphasized the western half of the island and are summarized below.

To assess if Puerto Rico was attached to the Caribbean plate, Jansma et al. (2000) compared the predicted velocity of the Caribbean with respect to the North American plate at the longitude of western Puerto Rico from the model of DeMets et al. (2000) against the velocity of western Puerto Rico relative to North America derived from GPS geodetic data. The predicted and GPS-derived velocities of the Caribbean with respect to North America for western Puerto Rico are 19.4±1.2 mm/yr toward N79°E±3° (1□) and 16.9±1.1 mm/yr with an azimuth of N68E±3 (1□), respectively, with the latter slightly slower and more northerly than that for Caribbean-North American plate motion as a whole. Thus nearly 85% of the relative motion between the Caribbean and North American plates is accommodated offshore northern Puerto Rico. Relative motion of western Puerto Rico with respect to the Caribbean as constrained by GPS geodesy is ~2.4±1.4 mm/yr to the west. The slow velocity of Puerto Rico with respect to the Caribbean has led some authors to assume that Puerto Rico is part of the Caribbean plate and to include sites in Puerto Rico in the formulation of the Caribbean reference frame (Weber et al., 2001). Although this interpretation is permissible given the errors associated with the geodetic data, it is likely that Puerto Rico is a discrete microplate. The most compelling evidence is seismicity associated with the Muertos Trough, which defines a pattern consistent with overriding of Caribbean lithosphere by southwestern Puerto Rico (Byrne et al., 1995; Dolan and Wald, 1998; McCann, in press). Our most recent GPS geodetic data, discussed herein, also support an independent PRVI.

To assess whether PRVI is rigid, Jansma et al. (2000) used the methodology of Ward (1990) to examine the dispersion of geodetic velocities about predictions of an angular velocity that best-fits those velocities. The results were only applicable to western Puerto Rico where the majority of sites were located. The average rate misfit to the 14 horizontal velocity components of the seven sites that were included (ARC1, GEOL, ISAB, MIRA, PARG, PUR3 AND ZSUA) was 1.2 mm/yr, with only two velocity components misfit by more than 2 mm/yr and one misfit at a level exceeding one standard error. The data were fit within their estimated uncertainties of 1-3 mm/yr. The approximate upper bound on the level of internal deformation of western Puerto Rico thus is 1-3 mm/yr. Uncertainties were on the order of several mm/yr for eastern Puerto Rico.

In contrast to western Puerto Rico where GPS velocities of PRVI with respect to the Caribbean are significant above error, the GPS-derived velocity at Virgin Gorda (GORD) at the eastern end of a presumed PRVI block (Figure 2) is zero within error to that predicted for the Caribbean plate at that location (DeMets et al., 2000; Jansma et al., 2000). The eastern Virgin Islands, therefore, may be attached to the Caribbean plate, implying no displacement along or across the eastern Anegada passage and a zone of EW extension of a few millimeters per year between Virgin Gorda and western Puerto Rico. The limited time series and geographic distribution of the network made these interpretations only tentative in Jansma et al. (2000). The objective of this study was to re-examine these conclusions with the additional geodetic data from new campaign and continuous sites, additional occupations for pre-existing campaign sites and the accumulation of two more years of data for CGPS sites.

The GPS-derived velocities relative to the Caribbean plate were consistent with W to SW motion of Hispaniola within the plate boundary zone at a faster rate than that of Puerto Rico, yielding EW extension of 3 to 5 mm/yr across the NS-trending Mona rift (Figure 2). The greater motion of Hispaniola with respect to the Caribbean (and, therefore, lower relative motion with respect to North America) within the plate boundary zone likely reflects collision with the Bahama Bank (Mann et al., 1995), a carbonate platform that extends northwest from the northern Dominican Republic to offshore Florida (Figure 1). In contrast, Puerto Rico has bypassed the collision and translates eastward with respect to North America at ~85% of the Caribbean-North American plate rate.

GPS data collection

Although the grant was not awarded until April 2000 in Puerto Rico and January 2001 in Arkansas, we report on data gathered since October 1999. During the 2000 calender year and subsequently in the 2001 and 2002 calender years, data were collected at 21 campaign sites in Puerto Rico and the Virgin Islands in addition to the three previously existing continuous sites (GEOL on the roof of the Physics building at UPRM and operated by us; PUR3 in western Puerto Rico and maintained by NOAA; and CRO1 in St. Croix and run by IGS). A continuous site was installed in Fajardo (FAJA) early in 1999, another was established in San Juan (UPRR) in October 2000 and yet another in Humacao (UPRH) in November 2000. Of the 21 campaign sites occupied in 2000, 2001, and 2002 nine were added to the network after the 1999 campaigns.

GPS measurements were first collected in the northeastern Caribbean in 1986 at six locations (Dixon et al., 1991), which subsequently were re-occupied as part of CANAPE (CAribbean-North American Plate Experiment) in 1994. The original sites were: Grand Turk (TURK), Turks and Caicos; Guantanamo (GTMO), Cuba; Cabo Rojo (ROJO), Capotillo

(CAPO), and Cabo Frances Viejo (FRAN) in the Dominican Republic, St. Croix (STCX), U.S. Virgin Islands, and Isabela (ISAB), Puerto Rico (Dixon et al., 1991). The network was densified during CANAPE and each subsequent year (for details, see Dixon et al., 1998; Jansma et al., 2000, Mann et al., 2002). Since 1994, measurements have been made on subsets of the entire network each year. A permanent IGS station was established in St. Croix in 1995 (CRO1) and a vector tie to the original 1986 site, STCX, was established (Dixon et al., 1998).

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 (San Juan), MONA (Mona island), DSCH (Desecheo island), ADJU (Adjuntas), ARC2 (Arecibo), CCM5 (Ponce), FAJA (Fajardo), LAJ1, LAJ2, and LAJ3 (Lajas Valley), SALN (Salinas), VIEQ (Vieques), and ANEG (Anegada, British Virgin Islands) and continuous sites GEOL in Mayagüez, FAJA in Fajardo, UPRR in Rio Piedras, and UPRH in Humacao operated by the Department of Geosciences, University of Arkansas, and PUR3 in Aguadilla maintained by the U.S. Coast Guard.

Details of the campaign observations from 1994 to 1999 can be found in Jansma et al. (2000). All campaign observations after 1999 were obtained with the following hardware: Trimble 4000 SSi 12-channel, dual-frequency code-phase receivers and Dorn-Margolin type choke ring antennae. Data were collected using either 0.5 m spike mounts or standard tripod/rotating optical plummet setups at a 30 s observation epoch and 10° elevation mask. An individual campaign occupation usually obtained between 10 to 24 hr of continuous data for 2-3 consecutive observation days. The descriptions of the continuous sites remain unchanged from that reported in Jansma et al (2000).

CGPS data from PUR3, GEOL, FAJA and CRO1 are included here. FAJA is a new CGPS site in northeastern Puerto Rico for which over two years of observations now exist. Two additional CGPS stations, UPRH (University of Puerto Rico, Humacao) and UPRR (University of Puerto Rico, Rio Piedras) have now been operating for a little more than one year. These sites have not yet accumulated enough data to merit serious analysis.

Data analysis

Data from continuous sites PUR3, GEOL, FAJA, and CRO1 and campaign sites ISAB, PARG, ADJN, ARC2, ZSUA, SALN, and GORD are considered. Although several additional campaign sites have been installed on PRVI since 2000, most have only had initial occupations completed. Others that have had a second occupation have only 1.5 to 1.8 years between observations, making estimates of their velocities too uncertain at this time. Data from a total of 11 sites are reported here.

All data were processed as free-network point positions using GIPSY-OASISII (v. 2.5.8a) (Lichten, 1990) on a Sun Microsystems UltraSPARC60 running Solaris 8. Free-network solutions were transformed, scaled, and rotated into ITRF00 (the current realization of the International Terrestrial Reference Frame, epoch 2000) using x-files from the Jet Propulsion Laboratory (Blewitt et al., 1992; Heflin et al. 1992). All processing used final, precise non-fiducial orbit, earth-orientation, and GPS clock files from JPL (300 s epoch). Time series velocity errors were calculated using the formulation of Mao et al. (1999), which includes both colored (time-correlated) and white noise contributions and an assumed estimate of $\sqrt{2}$ mm/yr of random monument noise. Scaled formal error estimates for individual site positions are not shown on the time series plots as their utility is limited. Component site velocities were calculated in ITRF00 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.

After obtaining an ITRF00 velocity for the latitude, longitude, and radial component and their associated errors, final velocities and errors in the Caribbean reference frame were calculated using the current best-fit model for Caribbean motion with respect to the ITRF00. The published version of the Caribbean reference frame is that of DeMets et al. (2000), which uses GPS-derived velocities from Aves Island (AVES) in the east, San Andres Island (SANA) in the west, St. Croix (CRO1) in the US Virgin Islands, and Cabo Rojo (ROJO) in the southern Dominican Republic (Figure 1). To supplement the limited geodetic data, azimuths of the eastern Swan Islands transform fault also are included to constrain Caribbean motion. An updated version of the reference frame incorporates Barbados (BARB, Figure 1) (DeMets et al., 2000 and personal communication) and is the one used here. CRO1 is the only continuous site and has been recording data since late 1995. Time series for the other sites range from 4 to 8 years. The best-fit angular velocity for the five Caribbean GPS sites yields an average residual velocity of 1.5 mm/yr. Caribbean fixed velocities include the full covariance of the individual sites velocities and the motion of the Caribbean plate at that location (DeMets et al., 2000, and personal communication). Velocities and their errors are shown with respect to ITRF00 and the Caribbean reference frame in Table 1. Error ellipses in figure 3 are 1σ and include both the error of the site time series and the Caribbean reference frame formulation.

GPS-derived velocities for Puerto Rico and the Virgin Islands

GPS-derived velocities relative to the Caribbean for PRVI appear consistent with a linear increase in velocity from near zero (1.7±2.1 mm/yr) at Virgin Gorda (GORD) in the east to ~3 mm/yr (3.0±0.3 mm/yr mean and standard deviation of the average of 5 sites) toward the west along the west coast of Puerto Rico (Figure 3a, Table 1). Although all PRVI velocities are similar within error, the systematic pattern suggests that the small differences are likely real, but they are close to the limits of detection in the current geodetic data. The new observations support earlier interpretations that PRVI may be attached to the Caribbean plate at GORD on its eastern end, requiring east-west extension across Puerto Rico and the western Virgin Islands (Jansma et al., 2000). The preliminary results were based on only 2 epochs (1994 and 1999) of data at GORD. The new dataset includes additional epochs at GORD in 2000 and 2001 and spans seven years. The inclusion of data from FAJA in the northeastern corner of Puerto Rico and from SALN in south-central Puerto Rico also strengthens this conclusion: the GPS-derived velocities of FAJA and SALN (average 2.2±0.3 mm/yr) relative to the Caribbean are faster than that of GORD, but slower than that of GEOL, PUR3, PARG, ADJN, and ARC2. The magnitude of the velocity of FAJA also is similar to the magnitude of that at ZSUA, ~35 km to the west. The azimuths vary by ~45°.

Comparison of the GPS-derived velocities relative to the Caribbean at GORD, SALN and FAJA provides important constraints for the neotectonics of the Anegada passage. At the longitude of GORD, where the velocity is near zero, little if any motion occurs across the Anegada passage. The possibility does exist that CRO1 and GORD velocities are affected by strain accumulation along a locked, fast-slipping, eastern Anegada passage fault. We believe this is unlikely, however, because of the similarity of CRO1's velocity with the other rigid Caribbean sites (AVES, SANA, ROJO, BARB). We note that CRO1 is closer to the Anegada passage faults than GORD and therefore should be more affected by any possible strain accumulation along these structures. Low levels of microseismicity south of the eastern Virgin Islands (Frankel et al., 1980) also support little motion between GORD and CRO1. To the west, however, where microseismicity is greater and motions of FAJA and SALN (average of 2.2±0.3 mm/yr) with respect to the Caribbean are toward the northwest and west, respectively (Figure 3), displacement across the northeast-trending structures of the Whiting and Virgin Island basins must have an extensional component, a conclusion supported by evidence of normal faulting documented in seismic profiles acquired in the Anegada passage (Jany et al., 1987; Holcombe et al., 1989; Masson and Scanlon, 1991). The change from near zero motion at GORD to 2.0±1.8 mm/yr relative to the Caribbean at FAJA (Figure 3a, Table 1) requires a component of northwest-southeast to east-west extension between the eastern Virgin Islands and eastern Puerto Rico. The NW-oriented velocity relative to the Caribbean of FAJA relative to the Caribbean yields northwest-southeast extension across the Anegada passage at the longitude of 65°W, whereas the W-directed velocity relative to the Caribbean of SALN produces near east-west extension across the Whiting and Virgin Islands basins south of Vieques. The westward motion of western Puerto Rico relative to the Caribbean of ~3 mm/yr implies a component of left-lateral strike-slip motion along either the east-west-trending Muertos trough or offshore faults south of Puerto Rico at the longitude of western and central Puerto Rico. Up to 2 mm/yr of convergence also is permitted along the Muertos trough within error (Figure 3a).

Implications for the rigidity of PRVI and displacement along subaerial faults

Although the GPS-derived velocities of sites in Puerto Rico and the Virgin Islands relative to the Caribbean are essential to constrain the kinematics of PRVI, the 1σ uncertainties associated with the individual site velocities frequently exceed geologically-based estimates of slip rates along those faults. To assess whether the small differences among the GPS-derived velocities for sites in Puerto Rico were geologically significant, we examined the evolution of component velocities and baseline lengths between several pairs of CGPS stations in the northeastern Caribbean. The campaign sites, PARG and ISAB, also were included in our analysis. The CGPS sites were selected because they have the longest time series, which generally should minimize the error associated with the calculations although as we will discuss below, CGPS data also may be biased. PARG and ISAB were included to provide baseline coverage of structures in southwest Puerto Rico. Relative velocity components (north, east, and up) (Table 2) and length were calculated among the CGPS sites and the ISAB and PARG campaign sites holding either GEOL, PUR3, or ISAB fixed in the ISAB-PARG baseline. Vectors shown in Figures 3b and 3c were determined by holding the ITRF00 position of one site fixed as a reference, GEOL in the case of the upper diagram, and determining the relative change for the north and east components for the other sites. Derived time series of the baseline components were then used to calculate component velocities. The full covariance for each component velocity in ITRF00 was included in the calculation of the standard deviation in fixed site component velocities reported in Table 2. The estimated component velocity errors already included our estimate of white time-correlated and monument noise. They do not include any provision, however, for error reduction as a result of common-mode noise in the time series and therefore are likely to be larger than the real errors for these site pairs.

To constrain the upper bounds of displacements along potentially active faults in western Puerto Rico, we examined two baselines: PUR3-GEOL, which extends north-south from the northwestern corner of the island to Mayagüez in the central western coast, and PUR3-PARG, which joins the northwestern and southwestern corners of Puerto Rico and crosses the seismically active Lajas Valley. PUR3-GEOL crosses the Great Southern Puerto Rico Fault Zone and the Cerro-Goden Fault (Figure 2). The length of the baseline between PUR3 and GEOL has remained constant within error during the six-year interval for which we have data (Table 2). The total integrated displacement across the GSPRFZ and the Cerro-Goden Fault, therefore, is less than the 0.5 mm/yr error along the baseline.

In contrast, the length of the baseline between PUR3 and PARG has decreased 1.6±0.3 mm/yr during the same time interval (Table 2). (The baselines ISAB-PARG and GEOL-PARG yielded similar results). Because PARG is a campaign site with only 6 epochs of observations, the errors associated with this baseline will be larger than those between two continuous sites. Nevertheless, the implication is that deformation ≤ 2 mm/yr is likely across southwestern Puerto Rico, a scenario that is not unreasonable given the high microseismicity in the Lajas Valley (Asencio, 1980). The decrease in line length implies shortening between PARG and GEOL. East-west trending faults that bound the Lajas Valley, therefore, likely have oblique-reverse motion. This is consistent with focal mechanisms derived by Doser et al. (in press).

The baselines GEOL-FAJA and PUR3-FAJA provide constraints on the overall deformation within and across Puerto Rico. GEOL-FAJA crosses both the Great Southern and Great Northern Puerto Rico Fault Zones, whereas PUR3-FAJA traverses only the latter (Figure 2). The time interval considered is April 1999 until December 2001, reflecting when the site at Fajardo was installed. During this period, the baseline length between GEOL-FAJA increased by

3.9±0.2 mm/yr r (Table 2). The length change for PUR3-FAJA is smaller, but still positive at 1.5±0.2 mm/yr, providing additional support for little displacement between GEOL and PUR3. While caution must be exercised when interpreting these data, the increasing baseline length and relative velocity (Figure 5b) between fixed GEOL or fixed PUR3 and FAJA imply a component of approximately ENE-WSW-oriented extension of between 1.5 and 3.9 mm/yr across the island of Puerto Rico. Whether this extension is accommodated along a few major structures (e.g. the Great Northern Puerto Rico Fault Zone where the extension would generate dextral transtension) or distributed across several smaller features is not clear. Higher than average levels of seismicity do occur along the central segment of the GNPRFZ (Asencio, 1980). The GPS-derived velocity relative to the Caribbean at ZSUA, a site between PUR3 and FAJA, is identical within error to that at FAJA, suggesting that the structures that take up displacement are located west of the San Juan metropolitan area. The errors associated with the GPS-derived velocities are still too large to conclude this definitively. We do note that there are several NS-trending valleys that channel the major rivers along the north coast of Puerto Rico; these may be manifestations of EW-oriented extension. One focal mechanism for the northwest corner of Puerto Rico is consistent with slip along NS-striking normal faults (Figure 1b). The observation of likely ENE to WSW extension across Puerto Rico is not surprising. Results from previous GPS studies and marine geophysical surveys document east-west extension between western Puerto Rico and eastern Hispaniola (van Gestel et al., 1998; Jansma et al., 2000; Mann et al., 2002). In addition, potential attachment of Virgin Gorda to the Caribbean at the eastern end of PRVI requires near east-west extension between the eastern Virgin Islands and eastern Puerto Rico. The GPS geodetic data suggest that east-west extension is not limited to the offshore regions, but affects the island of Puerto Rico. Orientations of T-axes from composite focal mechanisms also indicate east-west extension across eastern Puerto Rico (McCann, 2000).

To investigate potential motion across and along the Anegada passage in more detail, we examined the change in baseline length between FAJA in the northeastern corner of Puerto Rico and CRO1 on the island of St. Croix within the stable interior of the Caribbean plate. This has the advantage of eliminating the errors introduced into the Caribbean reference frame imposed by variations in velocities among the five stable Caribbean sites. Baseline length increased at 1.9±0.2 mm/yr (white noise; fit residuals) to 2.0±2.3 mm/yr (relative velocities with errors propagated) (Table 2), implying active extension across the Anegada passage, which is consistent with mapped structures in the offshore (Jany et al., 1987; Holcombe et al., 1989; Masson and Scanlon, 1991). A component of left-lateral strike-slip motion (1.2±1.3 mm/yr) is also permissible within error from the baseline component and fixed site velocity analysis. A pair of focal mechanisms immediately south of the Anegada passage are consistent with left-lateral strike-slip faulting along EW-oriented vertical planes (Figure 1b).

Conclusions

Using GPS geodetic data collected throughout the northeastern Caribbean from 1994 until 2002, we are able to refine the velocities of Puerto Rico and the Virgin Islands with respect to the Caribbean plate, to constrain maximum displacement rates along active faults on the island of Puerto Rico and immediately offshore and to examine potential diffuse extension between the Virgin Islands and eastern Puerto Rico. The data are consistent with east-west extension of several mm/yr in the boundary zone between the North American and Caribbean plates from eastern Hispaniola to the eastern Virgin Islands. The amount of extension increases westward with the most, 3-5 mm/yr, accommodated in the Mona rift between the Dominican Republic and western Puerto Rico. East-west extension of 1-3 mm/yr per year also acts across the island of Puerto Rico. Whether this extension is localized along a few structures or is broadly distributed is unknown. We note that re-activation of the Great Northern and Great Southern Puerto Rico fault zones would yield oblique-normal slip with right-lateral sense along these structures. A zone of east-west extension of up to 2 mm/yr also must exist between eastern Puerto Rico and Virgin Gorda, which likely is attached to the Caribbean plate. These extensional belts allow eastward transfer of slip between North America and the Caribbean from the southern part of the plate boundary zone (Enriquillo fault in the southern Dominican Republic) to the northern (Puerto Rico trench offshore northern Virgin Islands). Increased seismicity in the Sombrero trend north of the northern and easternmost Virgin Islands (Figure 2) is consistent with this interpretation.

The GPS-derived velocities of sites in Puerto Rico relative to the Caribbean (3.0±0.3 mm/yr), coupled with baseline changes between selected stations, constrain maximum displacement rates along active faults on the island and immediately offshore. Motions along or across any of the subaerial structures of Puerto Rico ≤ 2 mm/yr. The Lajas Valley in the southwest, where microseismicity is greatest, is the locus of highest permissible on-land deformation. Northwest-southeast to east-west extension of up to 2 mm/yr is also observed across the Anegada Passage.

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DATA AVAILABILITY

The campaign and continuous GPS data are being archived locally and backed up to DAT and CD. UPRM/UA raw data are not yet publicly available by ftp, because security issues regarding full public access have not been worked out and dedicated computational resources for such public access are not available at this time. Currently, all UPRM/UA GPS data through October 2001 have been placed in the UNAVCO archive following the standard procedures established by the GPS community. PUR3 and CRO1 data are avaliable on-line through the standard archives.

	Latitude North	Longitude East	Time Span (years)	Velocity North (ITRF2000) mm/yr	Velocity East (ITRF2000) mm/yr	Velocity North (Caribbean) mm/yr	Velocity East (Caribbean) mm/yr	Correlation coefficient (ITRF2000)
ADJN	18.17	292.20	4.211	11.4 ± 2.1	7.4 ± 2.8	-0.6 ± 2.2	-3.2 ± 2.9	0.0000
ARC2	18.34	293.25	3.181	11.6 ± 2.7	6.8 ± 3.6	-0.4 ± 2.7	-3.8 ± 3.7	0.0000
CRO1	17.76	295.42	6.216	12.5 ± 0.9	9.8 ± 1.1	-0.3 ± 1.5	-1.2 ± 1.4	0.0157
FAJA	18.38	294.38	2.301	13.7 ± 1.5	9.2 ± 1.6	1.4 ± 1.7	-1.4 ± 1.8	0.0224
GEOL	18.21	292.86	5.290	11.9 ± 1.0	7.3 ± 1.4	0.1 ± 1.2	-3.3 ± 1.6	-0.0230
GORD	18.43	295.56	7.214	13.5 ± 1.5	9.1 ± 1.9	0.6 ± 1.6	-1.6 ± 2.1	0.0000
ISAB	18.47	292.95	7.488	12.4 ± 1.3	7.5 ± 1.8	0.5 ± 1.4	-3.0 ± 2.0	0.0000
PARG	17.97	292.96	5.750	12.7 ± 1.6	8.2 ± 2.2	0.8 ± 1.7	-2.5 ± 1.7	0.0000
PUR3	18.46	292.93	4.556	11.9 ± 1.1	7.9 ± 1.2	0.1 ± 1.2	-2.6 ± 1.5	0.0312
SALN	18.03	293.77	1.768	12.1 ± 4.9	8.3 ± 6.4	-0.1 ± 5.0	-2.4 ± 6.5	0.0000
ZSUA	18.43	294.01	6.406	12.0 ± 1.5	9.0 ± 2.0	-0.3 ± 1.6	-1.6 ± 2.2	0.0000

Table 1: Velocities of GPS sites in Puerto Rico and the Virgin Islands in ITRF2000 and with respect to the stable Caribbean. For definition of stable Caribbean, see text. Uncertainties are 1σ and include white noise, flicker noise, and monument error.

Baseline	Fixed Site	Velocity North, (mm/yr)	Velocity East, (mm/yr)	Correlation coefficient
GEOL-PUR3	GEOL	0.02 ± 1.49	0.10 ± 1.84	-0.0328
GEOL-PARG	GEOL	3.34 ± 1.89	-1.26 ± 2.61	-0.0123
GEOL-FAJA	GEOL	1.85 ± 1.80	3.74 ± 2.10	-0.0368
GEOL-CRO1	GEOL	0.56 ± 1.38	2.66 ± 1.75	-0.0485
PUR3-PARG	PUR3	1.31 ± 1.94	-0.26 ± 2.51	-0.0274
PUR3-FAJA	PUR3	1.58 ± 1.86	1.49 ± 2.00	-0.0426
PUR3-CRO1	PUR3	0.36 ± 1.45	1.99 ± 1.60	-0.0538
FAJA-CR01	FAJA	-2.13 ± 1.77	0.96 ± 1.92	-0.0508
ISAB-PARG	ISAB	0.47 ± 2.06	-1.07 ± 2.84	-0.0027

Table 2: Baseline velocity components for selected pairs of GPS sites in Puerto Rico and the Virgin Islands. Changes are expressed in terms of velocity north and velocity east in mm/yr. Stated error is 1σ error propagated from ITRF2000 time series component errors without any provision for common mode errors. It is likely that these stated uncertainties substantially overestimate the real uncertainties.

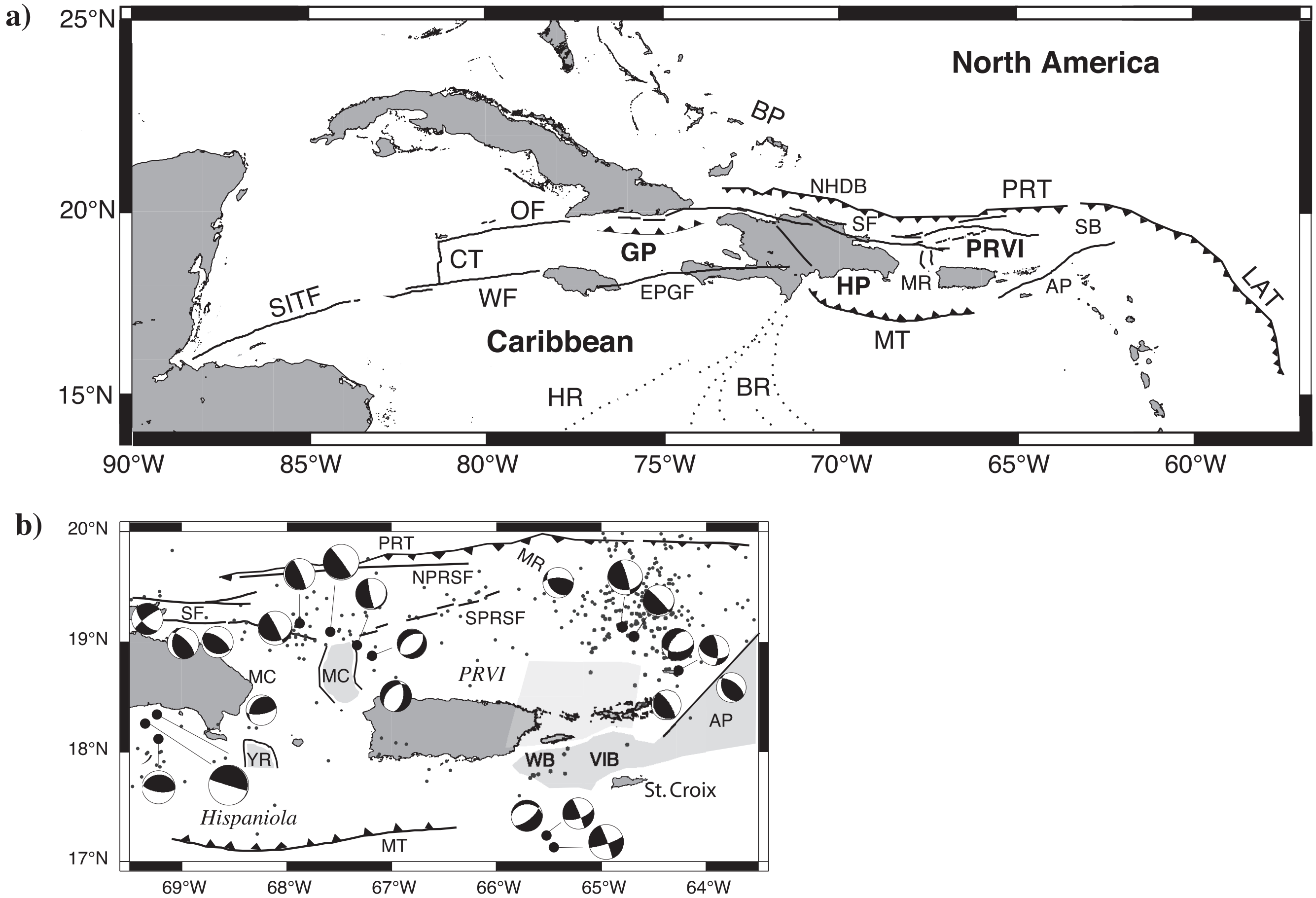

Figure 1: a) Map of northern Caribbean plate boundary showing microplates and structures. AP: Anegada Passage; BP: Bahamas Platform. BR: Beata Ridge. CT: Cayman Trough Spreading Center. EPGF: Enriquillo-Plantain Garden Fault. GP: Gonave Platelet. HP: Hispaniola Platelet. HR: Hess Rise. LAT: Lesser Antilles Trench. MR: Mona Rift. MT: Muertos Trough. NHDB: North Hispaniola Deformed Belt. OF: Oriente Fault. PRT: Puerto Rico Trench. PRVI: Puerto Rico-Virgin Islands block. SB: Sombrero Basin. SITF: Swan Islands Transform Fault. SF: Septentrional Fault. SPRSF: South Puerto Rico Slope Fault. WF: Walton Fault. **b)** Focal mechanisms for < 35 km for easternHispaniola, Puerto Rico and Virgin Islands. Sources are the Harvard CMT catalogue, the Puerto Rico Seismic Netowrk, Deng and Sykes (1995), and Molnar and sykes (1969). Dots are USGS epicenters for earthquakes above depths of 60 km with magnitudes > 3.5 from 1/1/1967 until 4/28/1999.

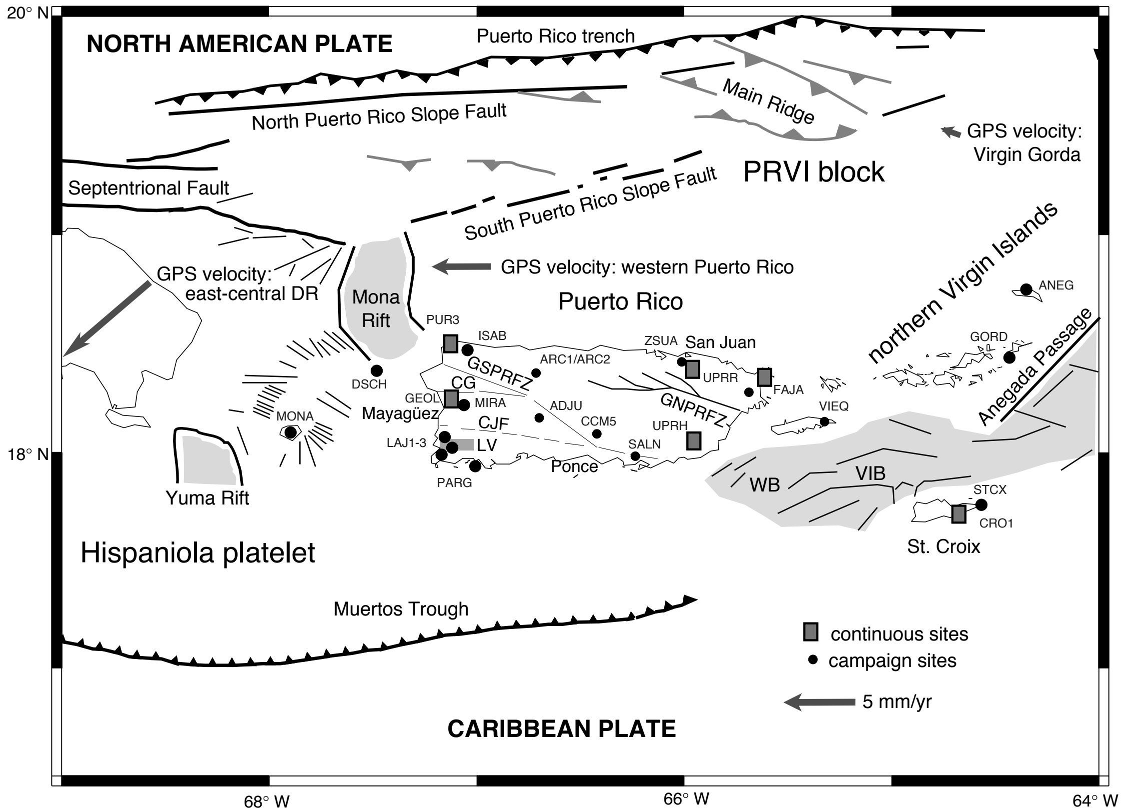

Figure 2: Current mixed-mode GPS geodetic network in northeastern Caribbean. GNPRFZ=Great Northern Puerto Rico Fault Zone. GSPRFZ=Great Southern Puerto Rico Fault Zone. CG=Cerro Goden Fault. CJF=Cordillera-Joyuda Faults. LV=Lajas Valley (gray shaded rectangle in SW Puerto Rico). WB: Whiting Basin. VIB: Virgin Islands Basin. Arrow in Dominican Republic is GPS-derived velocity relative to Caribbean for central Hispaniola, south of Septentrional Fault. Arrow north of Puerto Rico is average GPS-derived velocity relative to the Caribbean for western Puerto Rico. Arrow north of Virgin Islands is GPS-derived velocity relative to the Caribbean for Virgin Gorda. Length of arrow in lower left is 5 mm/yr for scale. Error ellipses not shown for clarity.

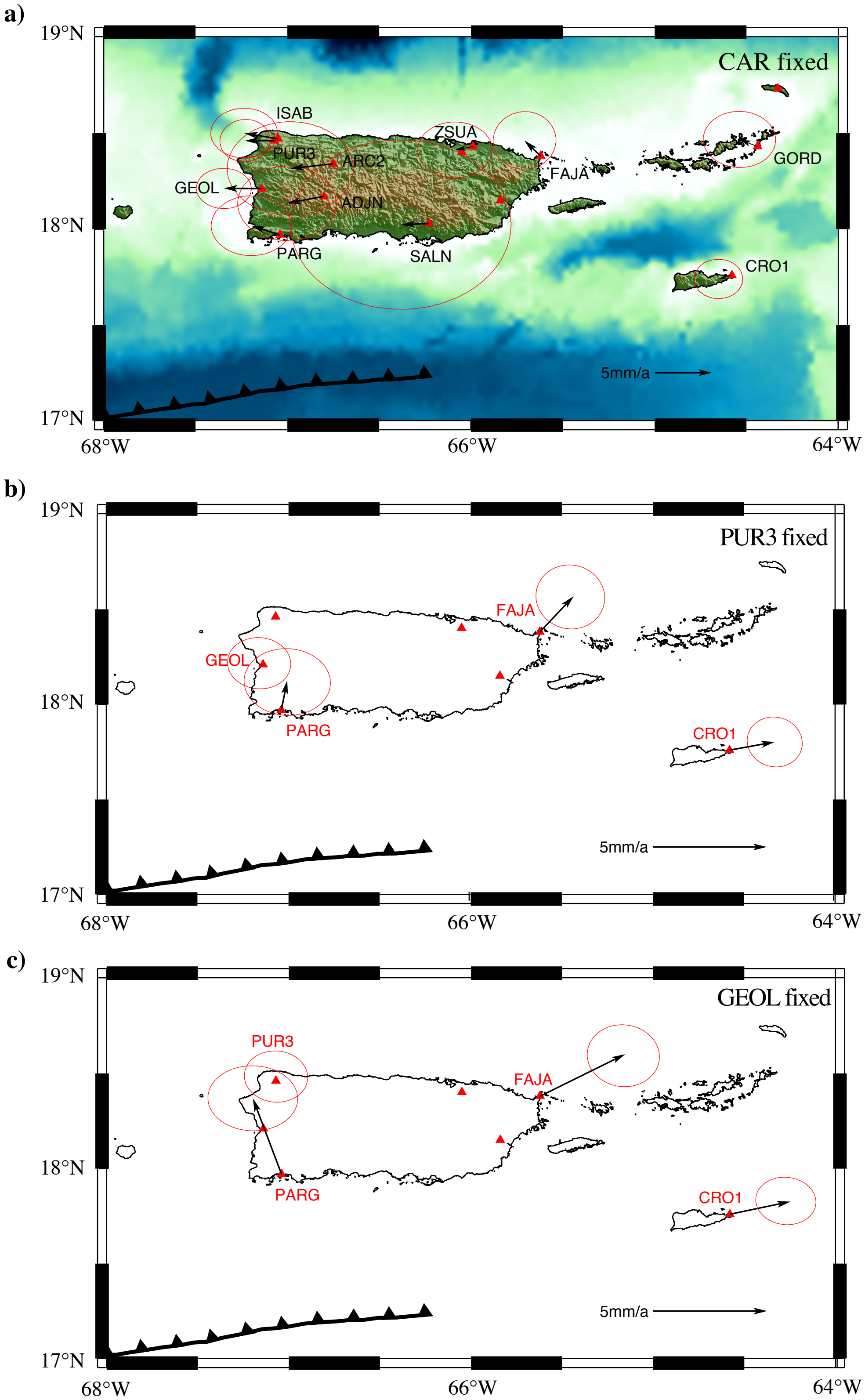

Figure 3: **a)** Velocities relative to Caribbean reference frame. Confidence ellipses are 1σ. Heavy black line with triangles offshore south of Puerto Rico represents the Muertos Trough. **b)** Velocities relative to fixed PUR3. For magnitude of changes along baselines see Table 2. **c)** Velocities relative to fixed GEOL. Table 2 lists velocities and 1σ for sites. Note that calculated 1σ errors were determined by propagating errors from the ITRF2000 time series component errors and likely are overestimates; therefore, error ellipses shown have been scaled to 0.5 1σ (both Figure 3b and 3c).