Neotectonics of Puerto Rico and the Virgin Islands, northeastern Caribbean, from GPS geodesy

Pamela E. Jansma[1,2], Glen S. Mattioli[1], Alberto Lopez[1], Charles DeMets[3], Timothy H. Dixon[4], Paul Mann[5], and Eric Calais[6]

Abstract. The boundary between the North American and Caribbean plates is characterized primarily by left-lateral motion along predominantly east-west striking faults. Seismicity and marine geophysical survey data are consistent with at least two, and possibly three, microplates in the diffuse boundary zone in the northeastern Caribbean: (1) the Gonave, (2) the Hispaniola, and (3) the Puerto Rico-northern Virgin Islands (PRVI). We discuss results from GPS geodetic measurements acquired since 1994 to test the microplate hypothesis, define PRVI translation and rotation within the boundary zone, and constrain PRVI neotectonics. GPS-derived velocities are analyzed with respect to both North American and Caribbean plate reference frames. Integrated displacements across PRVI are limited to a few millimeters per year, consistent with a rigid PRVI and permitting calculation of an average velocity for PRVI. The motions of PRVI relative to North America and the Caribbean are 16.9±1.1 mm/yr toward N68°E±3° (1σ) and 2.4±1.4 mm/yr toward S79°W±26° (1σ), respectively. In contrast with some recent models, ongoing rotation of PRVI about a nearby (< 25° distant) vertical axis is not supported by the geodetic data. In addition, we argue against eastward tectonic escape of PRVI and favor a simple, progressive increase in velocity across the plate boundary zone, requiring that the summed magnitude of strike-slip fault slip rates will equal the total plate motion rate between the Caribbean and North America. GPS data are consistent with components of left-lateral strike-slip faulting along the Muertos trough south of Puerto Rico and shortening across the Puerto Rico trench. Comparison of GPS velocities for PRVI with respect to North America with total North America-Caribbean relative motion suggests up to 85% of North American-Caribbean plate motion is accommodated by the Puerto Rico trench and offshore faults north of Puerto Rico. Differences in GPS-derived velocities from Hispaniola and PRVI yield east-west extension across the N-S trending Mona rift of a few millimeters per year when estimated elastic strain accumulation effects along the north Hispaniola deformed belt and the Septentrional fault zone are considered. The opening rate implies an age of the Mona rift of 2-3 million years, agreeing with marine geophysical data that support a young age for the structure.

1. Introduction

Tectonic models for the northern Caribbean [e.g., *Byrne et al.*, 1985; *Mann et al.*, 1995] propose active microplates within the plate boundary zone on the basis of geologic and earthquake evidence, but no previous studies have attempted to use geodetic data to isolate microplate motion in the region. In this paper, we apply GPS geodesy to test for the presence of an independently moving Puerto Rico-northern Virgin Islands (PRVI) microplate and to define its translation and rotation rates with respect to the larger, adjacent North American and Caribbean plates.

The boundary between the North American and Caribbean plates is characterized primarily by left-lateral motion along predominantly east-west striking faults (Figure 1). In the west the structure is relatively simple, consisting of the Swan and Oriente transform faults, which define the E-W trending Cayman trough and bound the short (~100 km), N-S trending mid-Cayman spreading center. In contrast, the eastern half of the boundary in Hispaniola, Puerto Rico and the Virgin Islands is a complex deformation zone ~250 km wide, whose northern and southern limits are defined by the Puerto Rico trench and the Muertos trough, respectively. Three proposed microplates lie within this diffuse boundary zone (Figure 1). From west to east, there are (1) the Gonave [*Mann et al.*, 1995], (2) the Hispaniola [*Byrne et al.*, 1985], and (3) the Puerto Rico-northern Virgin Islands (PRVI) [*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 (Figure 1). Both rotation about a nearby vertical axis [*Masson and Scanlon*, 1991] and tectonic escape to the east [*Jany et al.*, 1987] have been proposed for PRVI. A rigorous test of the

[1]Department of Geology, University of Puerto Rico, Mayagüez.
[2]Now at Department of Geosciences, University of Arkansas, Fayetteville.
[3]Department of Geology and Geophysics, University of Wisconsin, Madison.
[4]Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, Miami, Florida.
[5]Institute for Geophysics, University of Texas at Austin.
[6]Geosciences Azur, Centre National de Recherches Scientifique, Valbonne, France.
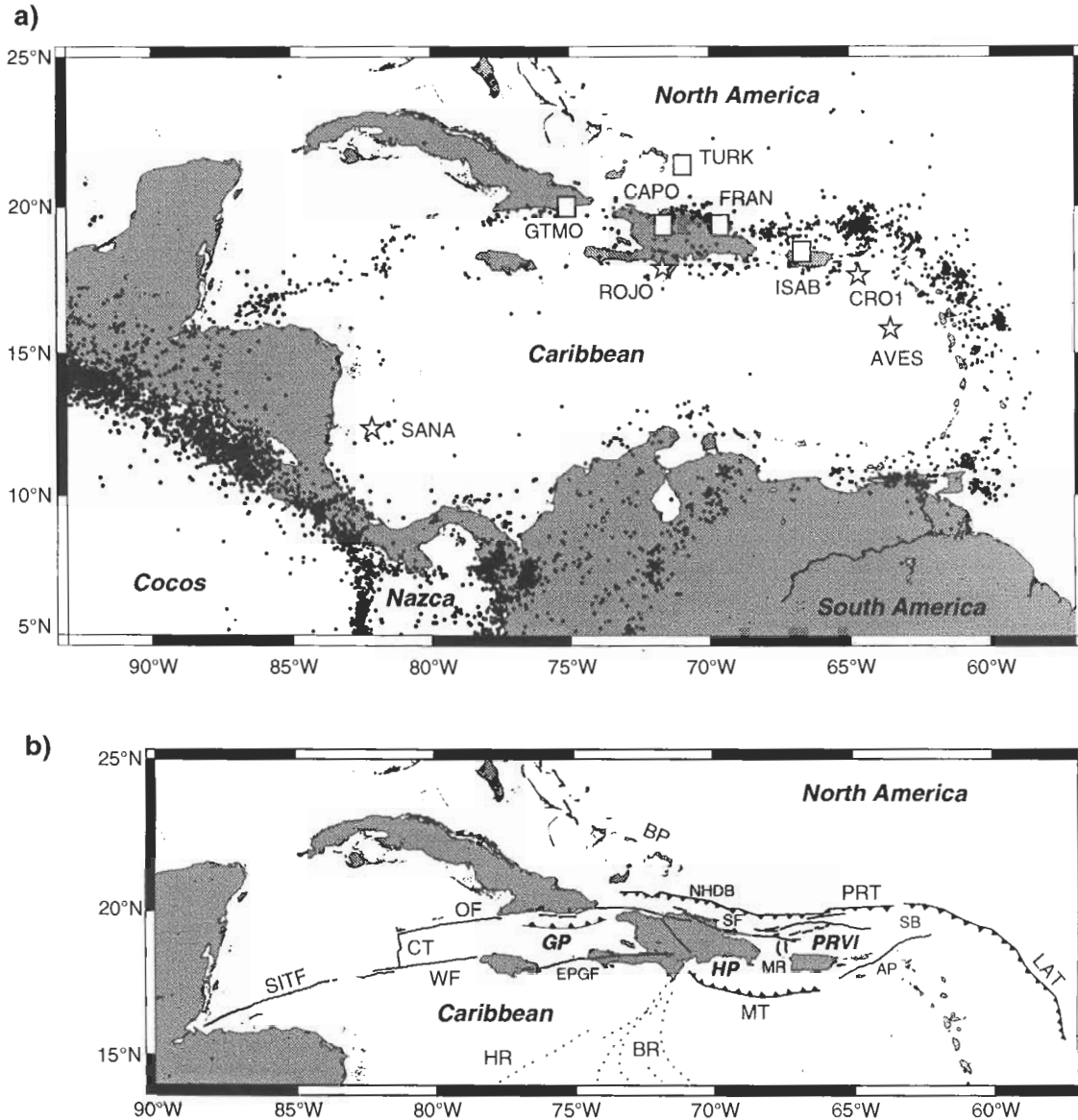
Figure 1. (a) Map of Caribbean plate and regional seismicity. Epicenters are for earthquakes above depths of 60 km with magnitudes > 3.5 from January 1, 1967, until April 28, 1999 (USGS). The four GPS sites used to constrain Caribbean reference frame are plotted as stars: SANA, San Andres Island; ROJO, Cabo Rojo. Dominican Republic; CRO1, St. Croix, US Virgin Islands; AVES, Aves Island. Original Caribbean-North America Plate Experiment (CANAPE) GPS sites are ROJO and CRO1 plus the five squares: CAPO, Capotillo. Dominican Republic; FRAN, Cabo Frances Viejo, Dominican Republic; GTMO, Guantanamo Bay. Cuba: ISAB, Isabela, Puerto Rico; TURK-Grand Turk, Turks and Caicos. (b) 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.

microplate hypothesis for the northeastern Caribbean, however, has not been conducted to date.

Global Positioning System (GPS) geodesy is a powerful tool that can be used to assess the presence of blocks and microplates and their independent motion [e.g., *Dixon et al.,* 2000] but, until recently, was limited in its application to plate boundary deformation in the northern Caribbean by insufficient data and lack of a well-defined Caribbean reference frame. These limitations have been steadily reduced by acquisition of GPS data at continuous stations installed in the

northern Caribbean between 1995 and 1997, through yearly campaigns since 1994, which capitalized on initial occupations at a few sites in 1986 [*Dixon et al.*, 1991, 1998], and by the development of a Caribbean plate reference frame from GPS geodetic measurements in the Caribbean interior [*DeMets et al.*, 2000]. These new data allow us to test the rigidity of a potential PRVI block and to constrain the kinematics of the northeastern corner of the Caribbean plate. We analyze GPS-derived velocities with respect to both North American and Caribbean plate reference frames to assess (1) rigidity of the PRVI block, (2) ongoing rotation of PRVI about a nearby (< 25°) vertical axis, (3) eastward tectonic escape of PRVI, (4) North American-Caribbean convergence across both the eastern Puerto Rico trench and Muertos trough, and (5) boundary parallel extension and the opening of the Mona rift.

2. Relative Motion Between the Caribbean and North American Plates

The relative motion of the Caribbean with respect to North America has been controversial, ranging from 11±3 mm/yr to the east as predicted from NUVEL-1A (Northwestern University Velocity Model 1A) [*DeMets et al.*, 1990] to 37±5 mm/year to the northeast as derived from earthquake slip vectors [*Sykes et al.*, 1982; *Deng and Sykes*, 1995]. GPS geodetic data from the Caribbean-North American Plate Experiment (CANAPE) constrain motion of the Caribbean plate with respect to North America at Cabo Rojo in the southern Dominican Republic as 20.6±1.2 mm/yr toward N89°E±3° (1σ) [*Dixon et al.*, 1998]. Incorporation of additional unpublished data from our 1998 observations decreases the rate slightly to

19.4±1.2 mm/yr and yields a revised azimuth toward N79°E±3° (1σ), in agreement with our earlier estimate within one standard error in rate and two standard errors in azimuth. Although the site at Cabo Rojo in the Dominican Republic is south of the southernmost strike-slip fault in the northern Caribbean plate boundary zone, the possibility exists of additional undocumented deformation in the offshore farther south [*Leroy and Mauffret*, 1996]. Recent GPS-derived velocities relative to North America from the interior of the Caribbean plate at San Andres Island in the west and Aves Island in the east, however, are similar to the velocity at Cabo Rojo within error in both rate and azimuth [*DeMets et al.*, 2000], supporting the assumption that the southern Dominican Republic is part of the Caribbean plate.

The NUVEL-1A velocity azimuth for Caribbean-North America relative motion is consistent with nearly pure left-lateral strike-slip displacement along plate boundary structures in the northeastern Caribbean, although minor convergence is allowed within the uncertainty. However, the velocity azimuths obtained from earthquake slip vectors [*Deng and Sykes*, 1995] and GPS data [*DeMets et al.*, 2000] are consistent with some transpression east of Cuba. Evidence for a component of convergence across the eastern Puerto Rico trench includes deep focus earthquakes defining dipping zones analogous to Wadati-Benioff zones, shallow thrust earthquakes, folds and thrust faults affecting young sedimentary rocks, and elevated topography [*Sykes et al.*, 1982; *Frankel*, 1982; *Mann and Burke*, 1984; *Byrne et al.*, 1985; *Stein et al.*, 1988; *Mann et al.*, 1990; *Rosencrantz and Mann*, 1991; *Calais and Mercier de Lepinay*, 1993; *Deng and Sykes*, 1995]. The convergence implied by these features, however, may record local block tectonics within the broad, deforming
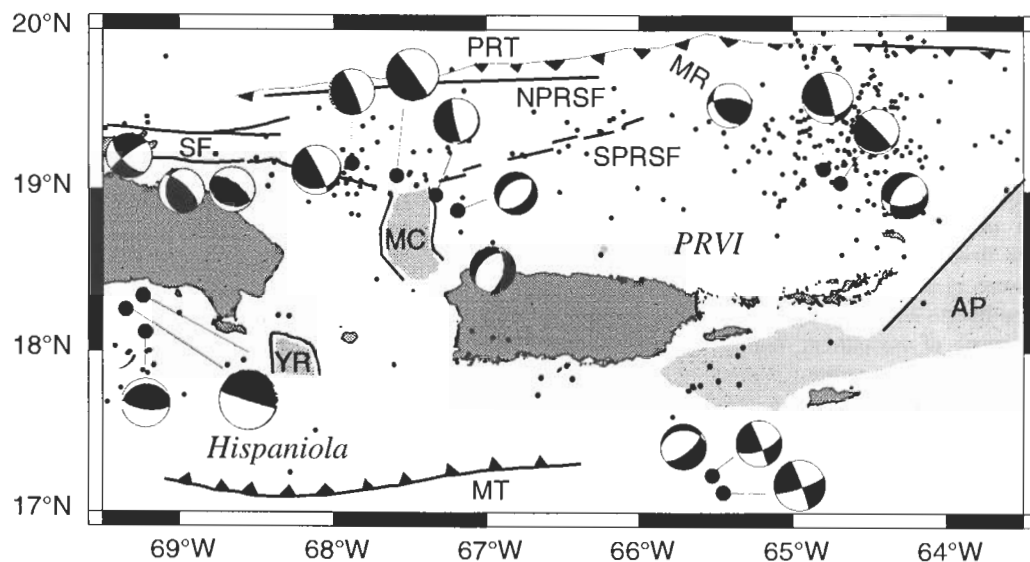

Figure 2. Focal mechanisms for depth < 35 km for eastern Hispaniola, Puerto Rico, and Virgin Islands. Sources are the Harvard Centroid Moment Tensor (CMT) catalogue, the Puerto Rico Seismic Network, *Deng and Sykes* [1995], and *Molnar and Sykes* [1969]. Dots are USGS epicenters for earthquakes above depths of 60 km with magnitudes > 3.5 from January 1, 1967, until April 28, 1999 (USGS). AP, Anegada passage; MR, Mona rift; MAR, Main ridge; MT, Muertos trough; NPRSF, north Puerto Rico slope fault; PRT, Puerto Rico trench; SF, Septentrional fault; SPRSF, south Puerto Rico slope fault; YR, Yuma rift.

plate boundary rather than relative motion of the rigid Caribbean plate with respect to North America. Indeed, eastern Hispaniola and PRVI are underthrust in the north and south by North American and Caribbean lithosphere, respectively, [*Dolan et al.*, 1998] and thus likely behave independently from the major plates.

3. Puerto Rico-Northern Virgin Islands Block (PRVI)

Seismicity within and around Puerto Rico and the Virgin Islands averages hundreds of earthquakes per year (Figures 1 and 2). Although most are small (< 4.0), several large events have occurred during historic times, including the 1916, 1918, and 1943 Mona passage earthquakes (Ms = 7.2, 7.3, and 7.5, respectively), 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]. With most events concentrated offshore, current seismicity mimics the pattern of the large, historic events (Figure 2), leading several workers to propose a rigid PRVI in the northeastern corner of the Caribbean [*Byrne et al.*, 1985; *Masson and Scanlon*, 1991].

The north side of PRVI is bounded by the east-west striking Puerto Rico trench, which lies ~100 km offshore, reaches a water depth > 8 km, and coincides with the largest negative free-air gravity anomaly on Earth (Figure 1). Despite recognition of this feature in the 1950s [*Officer et al.*, 1957] the nature of deformation in the Puerto Rico trench remains controversial. Oblique convergence across the Puerto Rico trench is supported by earthquake slip vectors, a diffuse zone of south dipping earthquakes below the island of Puerto Rico, and low-angle thrusts imaged in seismic profiles of the western Puerto Rico trench [*Sykes et al.*, 1982; *McCann*, 1985; *Deng and Sykes*, 1995; *Larue and Ryan*, 1998]. In contrast, *Speed and Larue* [1991] and *Masson and Scanlon* [1991] inferred extension across the trench offshore northwestern Puerto Rico from evidence of subsidence since the Pliocene of the northern insular shelf of Puerto Rico implied by Miocene shallow water limestones in water depths of 5000 m [*Moussa et al.*, 1987]. Although our previous GPS-derived velocities [*Dixon et al.*, 1998] indicated motion along the Puerto Rico trench as largely left-lateral strike slip, we were not able to differentiate within error between minor convergence or divergence across the structure. The Puerto Rico trench is traditionally assumed to accommodate much of the current highly oblique North American-Caribbean relative plate motion. Additional mapped offshore faults between the north coast of Puerto Rico and the Puerto Rico trench, such as the south Puerto Rico slope fault (SPRSF), however, also may take up some displacement [*Grindlay et al.*, 1997].

The Muertos trough, an east-west striking bathymetric feature of > 5 km depth, defines the southern limit of PRVI (Figure 1). A north dipping zone of earthquakes to a depth of 100 km and an accretionary prism along the lower slope south of southeastern Hispaniola and southwestern Puerto Rico are consistent with overriding of Caribbean lithosphere by southwestern PRVI along the Muertos trough [*Ladd et al.*, 1977; *Byrne et al.*, 1985; *Larue and Ryan*, 1990; *McCann*

and Pennington, 1990; *Masson and Scanlon*, 1991; *Deng and Sykes*, 1995]. Eastward along PRVI, ongoing subduction of Caribbean lithosphere is less clear. Indeed, *Malfait and Dinkelman* [1972] and *Burke et al.* [1978] argued that subduction ended in the Oligocene. Side-scan sonar images show that the accretionary prism narrows eastward and disappears near 65°W, southwest of St. Croix [*Mauffret and Jany*, 1990; *Masson and Scanlon*, 1991]. A minimum of 40 km of underthrusting is proposed at 68.5°W, whereas no underthrusting is thought to have occurred at 65°W [*Ladd et al.*, 1977], implying an eastward decrease in convergence across the Muertos trough [*Masson and Scanlon*, 1991].

To the west, PRVI is separated from Hispaniola by the Mona passage (Figure 2). Studies of seafloor structure [*Larue and Ryan*, 1990; 1998; *van Gestel et al.*, 1998] suggest E-W extension occurs in this region with the formation during the last few million years of the N-S trending Mona rift offshore northwestern Puerto Rico. A significant earthquake in 1918 (Ms = 7.3) in this area was accompanied by a 4-6 m tsunami in western Puerto Rico. Rupture along four segments of a N-S trending normal fault in the Mona rift were used in numerical simulations of tsunami run-ups in western Puerto Rico [*Mercado and McCann*, 1998]. The model yielded results in reasonable agreement with observed accounts of the tsunami, supporting the normal motion mechanism and thus the assumption of active extension in the Mona rift. Focal mechanisms of some more recent events offshore northwestern Puerto Rico are consistent with normal faulting along NNE striking planes (Figure 2). The nature of the putative boundary between the PRVI and Hispaniola microplates south of the Mona rift is unclear. The N-S oriented Yuma rift has been mapped southwest of the Mona rift (Figure 2) [*Jany et al.*, 1987; *Grindlay et al.*, 1997], but the kinematics of the structure are not well constrained. Side-scan images support continuity of the Muertos trough from southeastern Hispaniola to southwestern Puerto Rico [*Jany et al.*, 1987].

Eastern PRVI is bounded by the ENE trending Anegada passage (Figure 2), which connects the Neogene Virgin Island and Whiting basins in the southwest (Figures 1 and 3) with the Sombrero basin in the northeast and defines a zone of probable transtension along which displacement from the eastern end of the Muertos trough is transferred to the Puerto Rico trench [*Jany et al.*, 1987; *Masson and Scanlon*, 1991]. Both right-lateral [*Nemec*, 1980; *Matthews and Holcombe*, 1976; *Jany et al.*, 1987] and left-lateral strike-slip components of motion have been proposed for the Anegada passage fault [*Hess and Maxwell*, 1953; *Donnelly*, 1964]. Dextral faulting implies eastward motion of PRVI faster than that of the Caribbean interior and supports tectonic escape of PRVI within the plate boundary zone. Shallow seismicity is localized along the edges of the Anegada passage (Figure 2), although most large historic events occurred north of the Virgin Islands [*Murphy and McCann*, 1979; *Frankel et al.*, 1980; *McCann*, 1985] and no earthquakes were recorded in the eastern Anegada Passage between 63.5° and 64.5°W by a local seismic network deployed in the Virgin Islands during the late 1970s [*Frankel et al.*, 1980]. Whether the lack of seismicity reflects long recurrence intervals or no displacement along the eastern portion of the Anegada fault is unknown. Events well north of the Anegada passage and the northern Virgin Islands record a
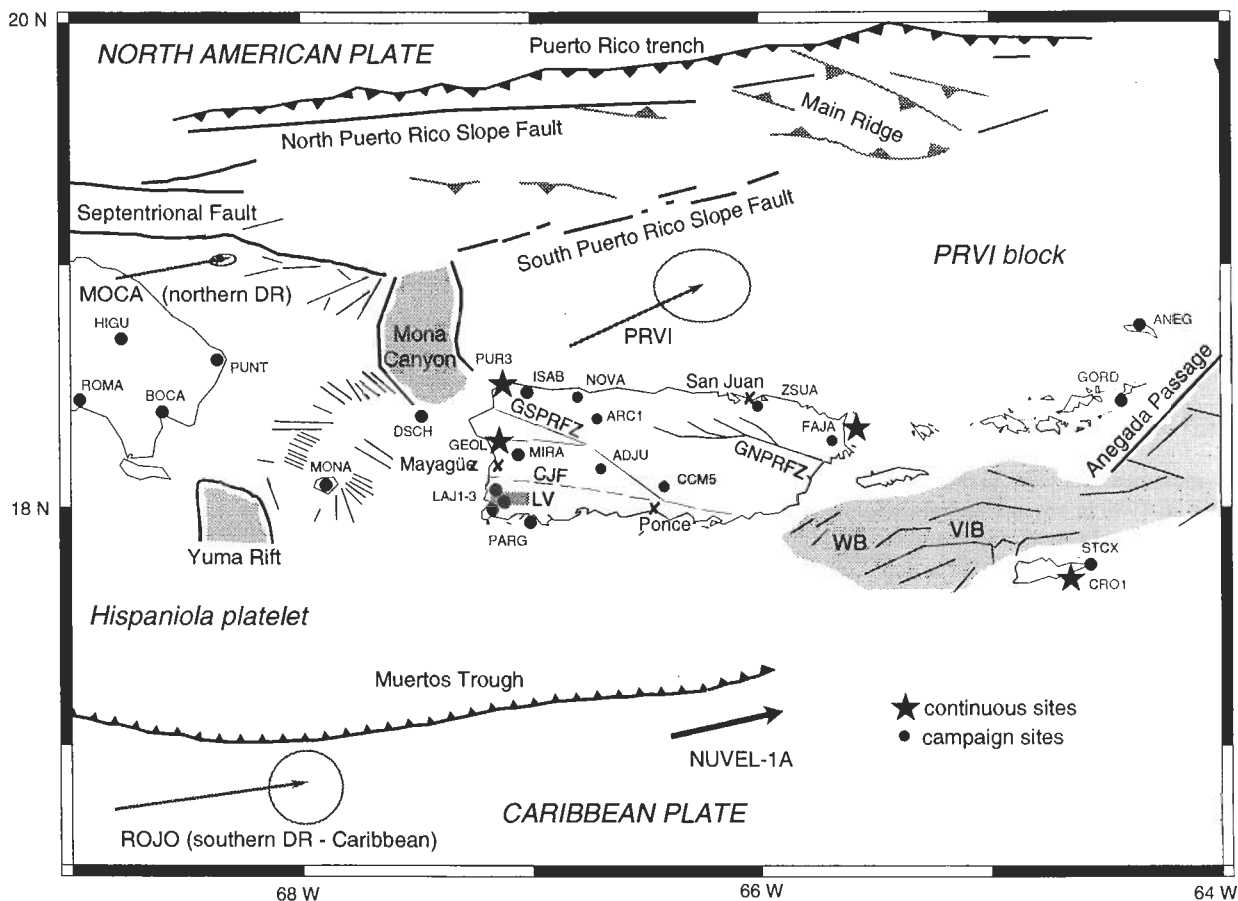
Figure 3. Current mixed mode GPS geodetic network in the northeastern Caribbean. GNPRFZ, great northern Puerto Rico fault zone; GSPRFZ, great southern Puerto Rico fault zone; CJF, postulated Cordillera-Joyuda faults; LV, Lajas Valley (medium gray shaded rectangle in southwestern Puerto Rico). Major offshore structures also are shown. Light gray shaded regions are zones of inferred extension. WB, Whiting basin; VIB, Virgin Islands basin. Arrows are GPS-derived velocities relative to North America and the NUVEL-1A velocity, derived from global plate motions, of the Caribbean with respect to North America. For scale, length of NUVEL-1A arrow corresponds to a rate of 11±3 mm/yr. Circles are 95% confidence limit. Error ellipse is not shown for NUVEL-1A for clarity.

combination of reverse and sinistral motion along roughly E-W striking faults, which is consistent with ENE directed relative motion of the Caribbean with respect to North America. The structural grain of the Anegada passage is dominated by NE/SW or E-W striking faults, which on seismic reflection profiles, clearly have a significant normal component [*Jany et al.*, 1987; *Holcombe et al.*, 1989; *Jany et al.*, 1987; *Masson and Scanlon*, 1991] requiring extension across the structure [*Speed and Larue*, 1991]. Throws along the major faults decrease southwestward to the Muertos trough from > 4 km to zero over a distance of 50 km, implying rapidly decreasing extension westward [*Masson and Scanlon*, 1991].

Some neotectonic models for PRVI advocate rigid body, counterclockwise rotation of PRVI about a vertical axis located either in southeast Puerto Rico or immediately offshore to the northeast in response to left-lateral motion along the North American-Caribbean plate boundary [e.g., *Masson and Scanlon*, 1991; *Huerfano*, 1995]. These models predict extension to the NW (Puerto Rico trench offshore northwestern

Puerto Rico) and SE (Anegada passage) and shortening to the NE (Puerto Rico trench offshore northeastern Puerto Rico) and SW (Muertos trough). The opening of the Mona rift is problematic in this interpretation.

A rotation model is supported by paleomagnetic data from Cretaceous and Eocene rocks exposed on Puerto Rico, which record > 45° and 24.5° of counterclockwise rotation since the Eocene and Miocene, respectively [*Fink and Harrison*, 1972; *Van Fossen et al.*, 1989; *Reid et al.*, 1991]. Because the paleomagnetic signature of Pliocene (4.5 m.y.) carbonates from northern Puerto Rico was not statistically different from that of the present, all the rotation observed in Miocene strata was assumed by *Reid et al.* [1991] to have occurred between 11 and 4.5 m.y. with no rotation occurring during the last few million years. This viewpoint is supported by *Larue and Ryan* [1998] and *van Gestel et al.* [1998], who argue, on the basis of evidence from seismic reflection profiles, that PRVI rotation stopped a few million years ago and that the current phase of deformation is contractional across the entire E-W

trending Puerto Rico trench, including the western segment offshore northwestern Puerto Rico. In their models, opening of the Mona rift occurs in response to eastward motion of a rigid PRVI during the last few million years. Collision with the Bahama Bank effectively pins Hispaniola and precludes its eastward displacement within the plate boundary zone, yielding extension between PRVI and Hispaniola. *Mauffret and Jany* [1990] also favor recent eastward tectonic escape of PRVI on the basis of fault patterns within the Anegada passage, which are compatible with dextral transtension [*Jany et al.*, 1987].

4. GPS Data Acquisition

GPS measurements were first collected in the northeastern Caribbean in 1986 at seven locations (Figure 1): 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]. These sites were reoccupied in 1994, and the network was densified to include an additional 15 sites in the Dominican Republic, Puerto Rico, and the Virgin Islands as part of CANAPE. Measurements were collected each year since 1994 on subsets of the network. In 1995, a permanent International GPS Service for Geodynamics (IGS) station was established in St. Croix (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 3) 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), ARC1 (Arecibo), CCM5 (Ponce), FAJA (Fajardo), LAJ1, LAJ2, and LAJ3 (Lajas Valley), and ANEG (Anegada, British Virgin Islands) and continuous sites GEOL in Mayagüez and FAJA in Fajardo operated by the Department of Geology, University of Puerto Rico, and PUR3 in Aguadilla maintained by the U.S. Coast Guard.

GPS campaign data were collected using two different receiver/antennae combinations. All observations from May 1994 to June 1996 were made using Trimble 4000 SSe 9-channel, dual-frequency, code phase receivers equipped with Trimble SST antennae with ground planes. All observations after June 1996, with the exception of the 1998 campaigns at SANA and AVES, were obtained with Trimble 4000 SSi 12-channel, dual-frequency, code phase receivers equipped with Trimble Dorn-Margolin type choke ring antennae. Data were collected and archived at a 30 s epoch using a 10° elevation mask. A minimum of 8 hours of GPS data per UTC observation day was collected during all campaign occupations. The majority of sites had significantly more data as a result of 16-24 hours of observations during each UTC day. Except for a brief period in October 1995, both anti-spoofing (A/S) and selective availability (S/A) were on during data acquisition. The University of Puerto Rico, Mayagüez (UPRM) (GEOL and FAJA), National Oceanographic and Atmospheric Administration (NOAA) (PUR3), and IGS (CRO1) continuous stations all have choke ring antennae and record at 30 s rate to 5° elevation. GEOL, FAJA, and PUR3 use Trimble 4000SSi receivers, while the CRO1 site is equipped with an AOA Turbo Rogue receiver.

Data from continuous sites PUR3, GEOL, and CRO1 (Figure 4) and campaign sites ISAB, PARG, MIRA, ARC1, ZSUA, and GORD (Figure 5) are considered in this paper. For the remaining sites, time series are not yet of sufficient duration to provide robust velocity solutions and they are not used in our analysis.

5. Data Analysis

GPS geodetic data were processed using the GPS inferred positioning system, orbit analysis, and simulation software package (GIPSY/OASIS II) developed, distributed, and supported by the NASA Jet Propulsion Laboratory (JPL) [*Lichten*, 1990]. Analysis was performed either at the University of Wisconsin or University of Puerto Rico, Mayagüez, using identical versions of GIPSY (version 2.5, update 8a) and processing scripts. Receiver independent exchange (RINEX) format data were processed with precise orbit and clock products from JPL [*Zumberge et al.*, 1997]. A nonfiducial point-positioning strategy was adopted for all station days, following *Dixon et al.* [1998]. Free-network solutions were transformed into the international terrestrial reference frame (ITRF96) [*Sillard et al.*, 1998] (Table 1) [e.g., *Blewitt et al.*, 1992; *Heflin et al.*, 1992]. Errors shown for daily site positions are scaled 1σ errors. Velocity estimates use a weighted least squares fit to daily site positions. Uncertainty on derived velocities reflects an estimate of both white and time-correlated noise, using the methodology of *Mao et al.* [1999].

6. GPS-Derived Velocities for Puerto Rico and the Virgin Islands

6.1. Microplate Rigidity, Translation, and Rotation

Before solving for the motion of sites in Puerto Rico and the Virgin Islands relative to the North American and Caribbean plates, we first use the velocities of GPS sites in Puerto Rico, expressed relative to ITRF96 (Table 1), to address two questions: Does the microplate deform internally, and do GPS velocities from Puerto Rico constrain all components of the motion of the PRVI microplate? The dispersion of geodetic velocities about the predictions of an angular velocity that best fits those velocities can be used to assess the rigidity of a plate [*Argus and Gordon*, 1996; *Dixon et al.*, 1996] or block [*Dixon et al.*, 2000], albeit only approximately when sites are located in the zone of elastic strain accumulation of an active fault. Using the method described by *Ward* [1990], we inverted horizontal velocities from ARC1, GEOL, ISAB, MIRA, PARG, PUR3, and ZSUA to find the weighted least squares best fit angular velocities for the seven sites. The average rate misfit to the 14 horizontal velocity components is 1.2 mm/yr, with only two velocity components misfit by > 2 mm/yr and one misfit at a level exceeding one standard error. The data are
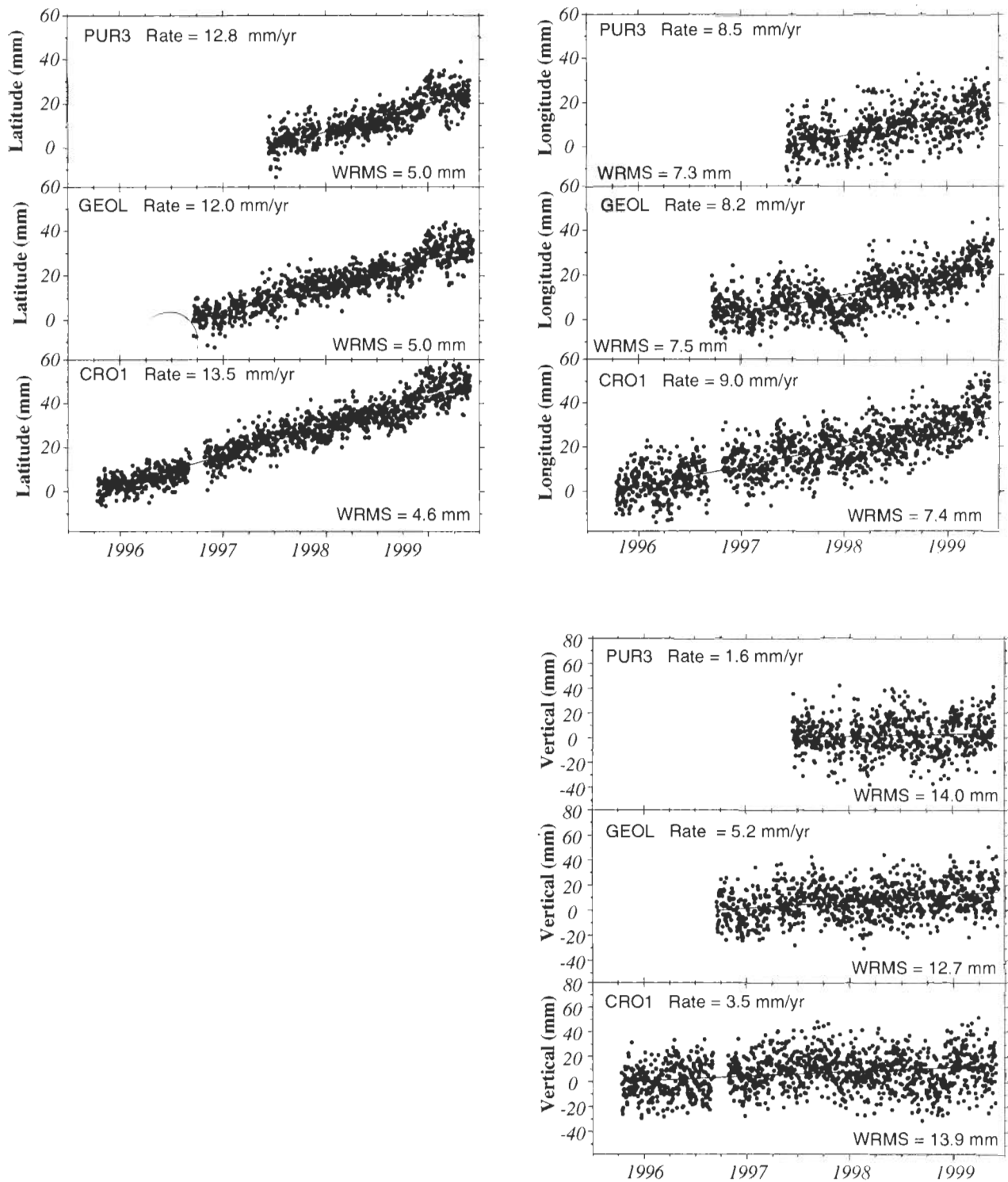
Figure 4. GPS station coordinate time series for continuous stations PUR3, GEOL, and CRO1. Daily point positions are in international terrestrial reference frame (ITRF96). Formal solution errors are not shown for clarity. Note the correlated noise among the three sites.
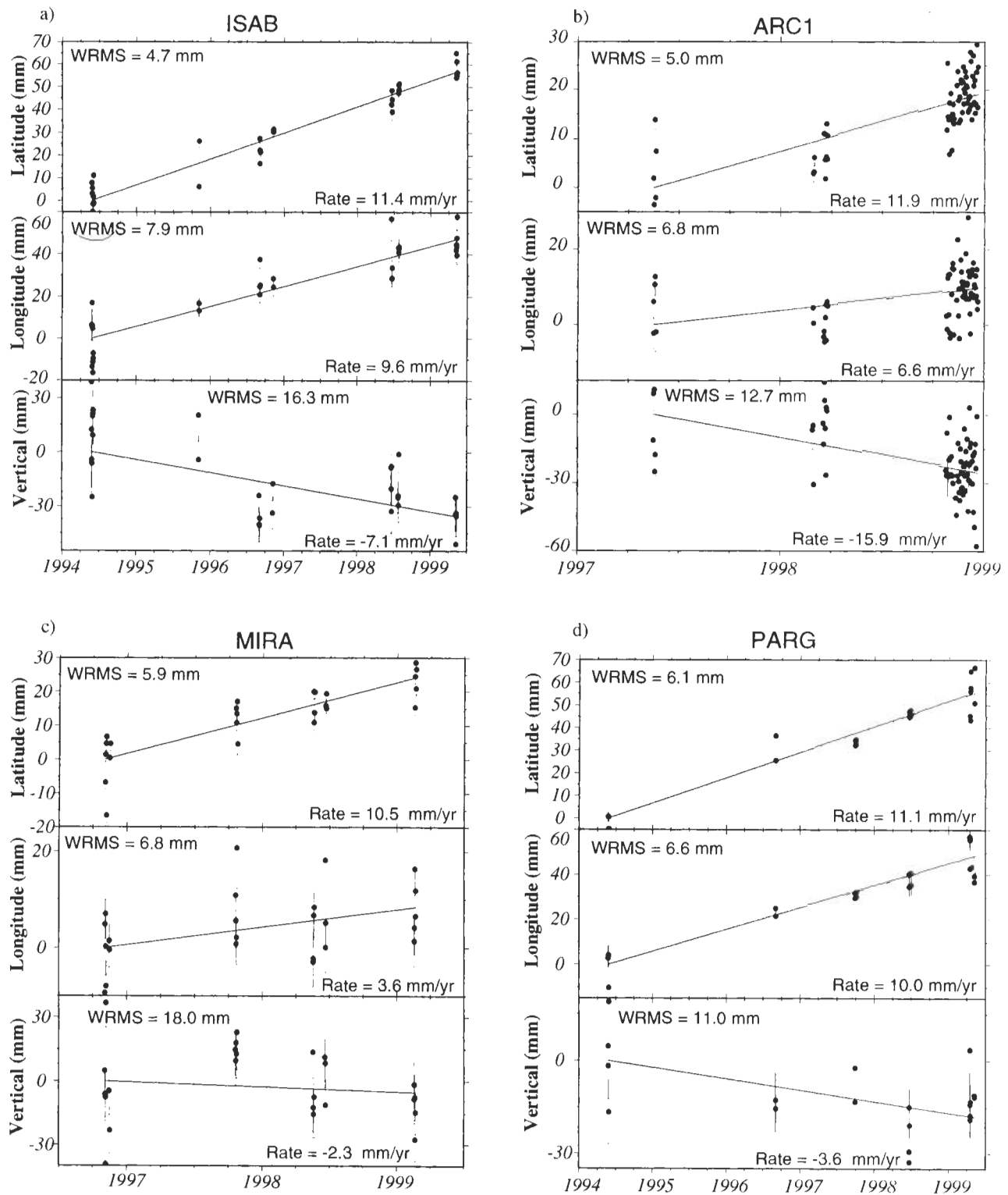
Figure 5. GPS station coordinate time series for PRVI campaign sites: ISAB, MIRA, PARG, ARC1. ZSUA. and GORD. Point positions are in ITRF96. Solution errors are scaled 1σ formal errors from GPS inferred positioning system, orbit analysis, and simulation software package (GIPSY/OASIS II).
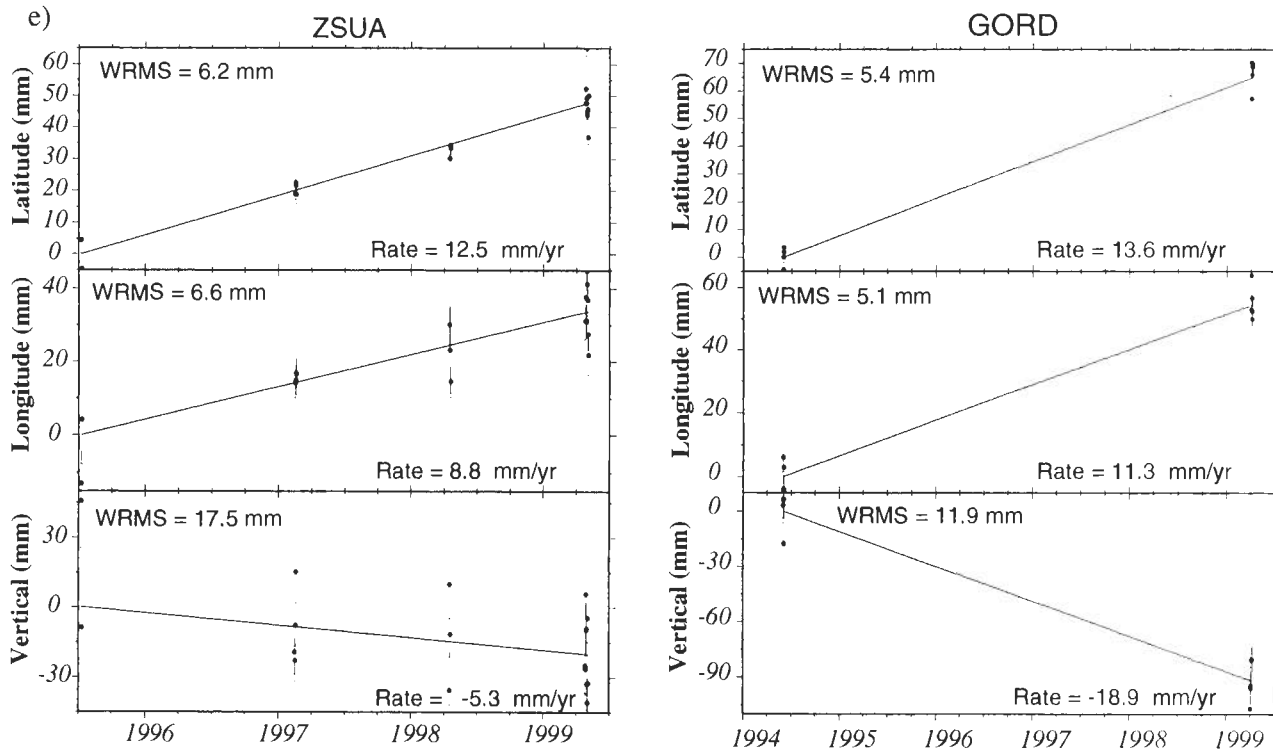
e)

Figure 5. (continued)

thus fit within their estimated uncertainties of 1-3 mm/yr, providing an approximate bound on the level of internal deformation of the PRVI microplate and suggesting that the block is rigid within our velocity uncertainties.

The GPS site velocities from the PRVI microplate constrain only the components of the angular velocity that predict the rate and direction of motion in western Puerto Rico, where all but one of the PRVI GPS sites are located. For example, the 1σ

uncertainties in the linear velocity predicted by the best fitting angular velocity achieve minimum values of ± 0.65 mm/yr and $\pm 2.8°$ in western Puerto Rico, but increase to ± 4 mm/yr and $\pm 5.5°$ in eastern Puerto Rico. Velocity uncertainties thus increase rapidly with angular distance from western Puerto Rico, as expected, given that the available data impose few or no constraints on motion outside of western Puerto Rico. Along the Muertos trough and Anegada fault, which separate

Table 1. Velocities of PRVI Sites and CRO1 in ITRF96[a]

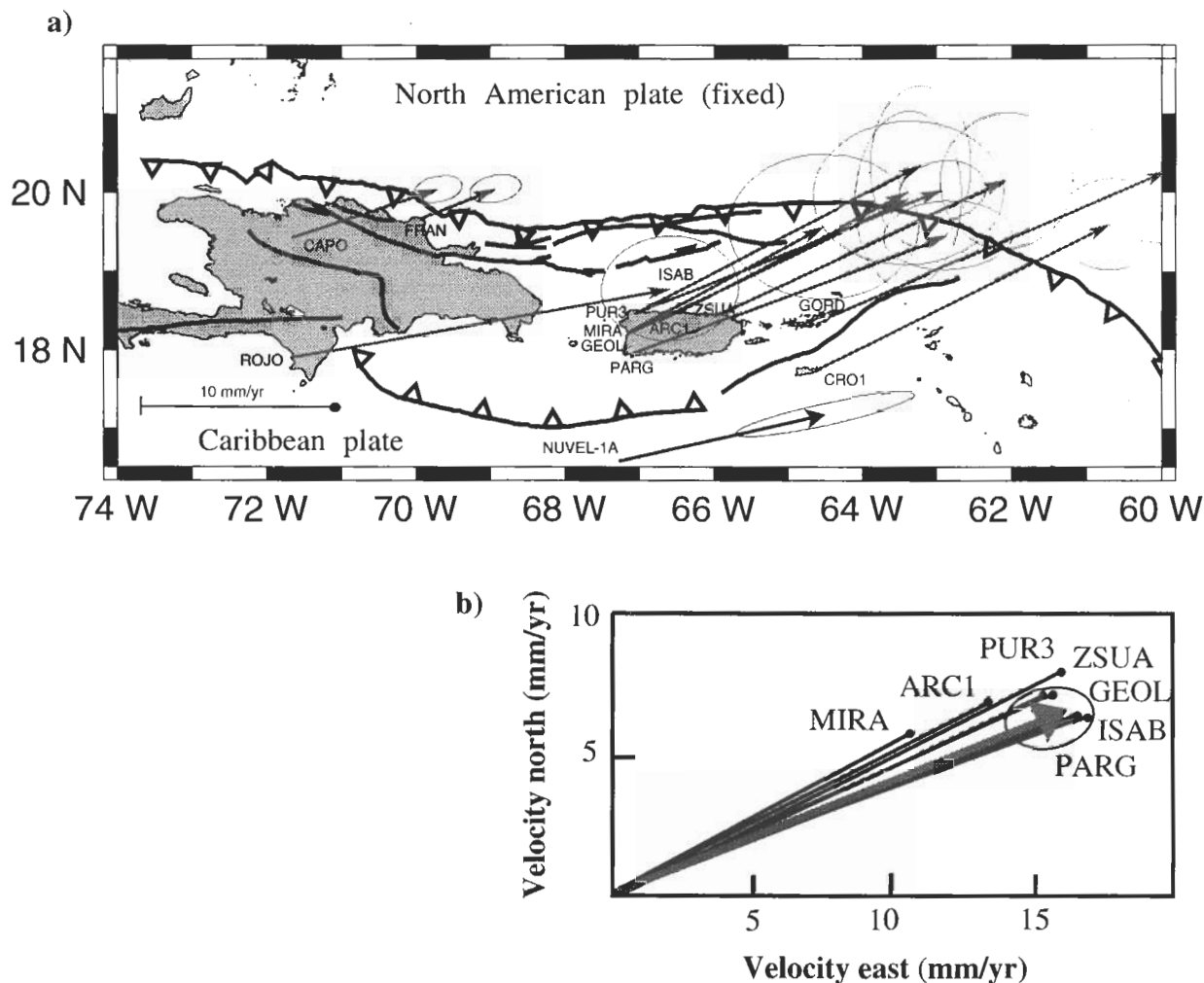|	Velocity North (ITRF96), mm/yr	Velocity East (ITRF96), mm/yr	Latitude, °N	Longitude, °E
ARCI	11.9 ± 2.5	6.6 ± 3.3	18.35	293.25
CRO1	13.5 ± 1.5	9.0 ± 1.8	17.76	295.42
GEOL	12.0 ± 3.1	8.2 ± 1.7	18.21	292.86
GORD	13.6 ± 2.5	11.3 ± 3.3	18.43	295.56
ISAB	11.4 ± 0.9	9.6 ± 1.3	18.47	292.95
MIRA	10.5 ± 2.5	3.6 ± 3.3	18.23	292.87
PARG	11.1 ± 1.1	10.0 ± 2.1	17.97	292.96
PUR3	12.8 ± 2.8	8.5 ± 1.6	18.46	292.93
ZSUA	12.5 ± 2.4	8.8 ± 2.2	18.43	294.01

[a] Uncertainties are 1 standard error.

a)

b)

Figure 6. (a) Velocities relative to fixed North America defined according to *DeMets and Dixon* [1999]. Confidence ellipses are two-dimensional 95%. (b) Velocities of PRVI sites relative to North America plotted at a common origin. Arrow is average PRVI velocity at MIRA derived from Puerto Rico-North America angular velocities and their covariances.

the PRVI microplate from the Caribbean plate, the 1σ uncertainties of several millimeters per year exceed geologically based estimates of slip rates along those faults.

Because the present velocities impose meaningful constraints on PRVI motion only in western Puerto Rico, we restrict the subsequent kinematic analysis as follows: predictions of the motion of the PRVI block relative to both the North American and Caribbean plates are made only for a point at the geographic center of the GPS sites in western Puerto Rico (18.3°N, 67.0°W). We then make the reasonable assumption that the block translates rigidly at the velocity of western Puerto Rico, supported by the fact that GPS site ZSUA in eastern Puerto Rico has a velocity similar to that for sites in western Puerto Rico. Well-constrained velocities from sites in eastern Puerto Rico are needed to test more rigorously for rotation of the PRVI block and to refine the interpretations presented below.

6.2 Velocities Relative to the North American Plate

To describe the velocities of GPS sites in the northeastern Caribbean relative to the North American plate (Figure 6 and Table 2), we use the angular velocity that describes motion of the North American plate relative to ITRF96 to predict the North America ITRF96 velocity at each of our GPS sites. We then subtract the predicted plate velocity at each site from the site velocity and sum the covariance that describes the uncertainties in both. The North American plate angular velocity we use is derived from the velocities of 16 continuously operating GPS stations in the stable interior of the North American plate [*DeMets and Dixon*, 1999].

GPS-derived velocities are similar for all sites in Puerto Rico at the 95% confidence limit (Figure 6). The mean velocity for motion of PRVI relative to North America, computed for western Puerto Rico, is 16.9±1.1 mm/yr toward N68E±3 (1σ).

Table 2. Velocities of PRVI Sites and CRO1 With Respect to Stable North America [a]

| | North America | |
	Velocity North, mm/yr	Velocity East, mm/yr
ARC1	6.9 ± 2.6	13.5 ± 3.4
CRO1	7.7 ± 1.6	15.7 ± 2.0
GEOL	7.1 ± 3.1	15.1 ± 1.9
GORD	7.8 ± 2.6	18.2 ± 3.4
ISAB	6.5 ± 1.1	16.6 ± 1.5
MIRA	5.6 ± 2.6	10.4 ± 3.4
PARG	6.2 ± 1.2	16.8 ± 2.8
PUR3	7.9 ± 2.9	15.5 ± 1.8
ZSUA	7.2 ± 2.4	15.7 ± 2.4

[a] Uncertainties are 1 standard error. Velocities and errors are based on values in Table 1.

We hereafter use this velocity to describe the motion of PRVI relative to North America. At the same location, a new Caribbean-North America angular velocity derived principally from GPS sites in North America and the Caribbean plate [*DeMets et al.*, 2000] predicts that motion of the Caribbean plate relative to North America is 19.2±1.3 mm/yr toward N69E±3 (1σ) (Figure 6b). The velocity of PRVI with respect to North America is thus 2 mm/yr slower than that of the Caribbean plate at this location. Motions relative to the Caribbean plate interior are discussed in section 6.3.

Comparison of Caribbean-North America motion in western Puerto Rico to the mean velocity of sites in western Puerto Rico suggests that a minimum of 85% of the total motion between the North American and Caribbean plates at the longitude of western Puerto Rico is accommodated by faults north of Puerto Rico with the remainder accommodated to the south of the island. We note that the azimuth of PRVI motion relative to North America (and that of rigid Caribbean with respect to North America) is parallel to the trend of earthquake slip vectors from the northeastern Caribbean [*Deng and Sykes*, 1995] and to the SPRSF [*Grindlay et al.*, 1997]. SPRSF is predominantly strike slip, whereas the Main ridge is a compressional feature oriented perpendicular to the PRVI-North America relative motion vector [*Muszala et al.*, 1999].

The GPS-derived velocity with respect to North America at GORD in the British Virgin Islands of 19.5±2 mm/yr toward N75E±5° (1σ) closely approximates the predicted relative motion between the rigid Caribbean and North American plates at GORD, 19.4±1.3 mm/yr toward N68E±3° (1σ), and differs from the velocity of western Puerto Rico, 16.9±1.1 mm/yr toward N68°E±3° (1σ). With only two epochs of observations at GORD, the difference in the rates relative to North America of GORD and PRVI is barely above the 2 mm/yr level of the noise associated with GPS geodetic data. More data in the Virgin Islands area will be required before we can assess

whether GORD is part of PRVI and intrablock deformation is several millimeters per year between eastern and western PRVI or whether PRVI encompasses only Puerto Rico and some portion of the eastern Virgin Islands and a tectonic break exists between GORD and eastern Puerto Rico. If the motion at GORD does prove to be the same as that at CRO1 over the long term (decade scale), the implication is that the eastern Virgin Islands are completely coupled to the Caribbean plate and that the displacement along the Anegada passage decreases to zero between eastern Puerto Rico and the eastern British Virgin Islands. The entire North American-Caribbean relative plate motion then must be accommodated north of the eastern Virgin Islands either by increased slip along the Puerto Rico trench or displacement along unmapped offshore faults. A zone of increased seismicity does occur along the Sombrero trend north of the northeastern Virgin Islands (Figure 2), where an earthquake swarm occurred in the late 1970s [*Frankel et al.*, 1980].

6.3 Velocities Relative to the Caribbean Plate

The velocities of sites in PRVI relative to the Caribbean plate are shown in Figure 7 and Table 3. Data used to define the velocity of the Caribbean plate relative to ITRF96 come from ROJO in the southern Dominican Republic, SANA on San Andres Island in the western Caribbean, AVES on Aves Island in the eastern Caribbean, and CRO1 on St. Croix (Figure 1). Our results do not change significantly if the CRO1 velocity is eliminated from the angular velocity solution. Details of the intraplate sites are given by *DeMets et al.* [2000] and are not repeated here. The methodology for generating a velocity relative to the Caribbean plate is analogous to that described above for deriving velocities relative to the

Table 3. Velocities of PRVI Sites and CRO1 With Respect to Stable Caribbean [a]

| | Caribbean | |
	Velocity North, mm/yr	Velocity East, mm/yr
ARC1	-0.1 ± 2.7	-4.3 ± 3.5
CRO1	0.4 ± 2.0	-2.4 ± 2.2
GEOL	0.2 ± 3.2	2.8 ± 2.1
GORD	0.5 ± 2.8	0.3 ± 3.5
ISAB	-0.4 ± 1.4	-1.2 ± 1.8
MIRA	-1.3 ± 2.7	-7.4 ± 3.5
PARG	-0.8 ± 1.5	-1.1 ± 2.4
PUR3	1.0 ± 3.0	-2.3 ± 2.0
ZSUA	0.1 ± 2.6	-2.1 ± 2.5

[a] Uncertainties are 1 standard error. Velocities and errors are based on values in Table 1.
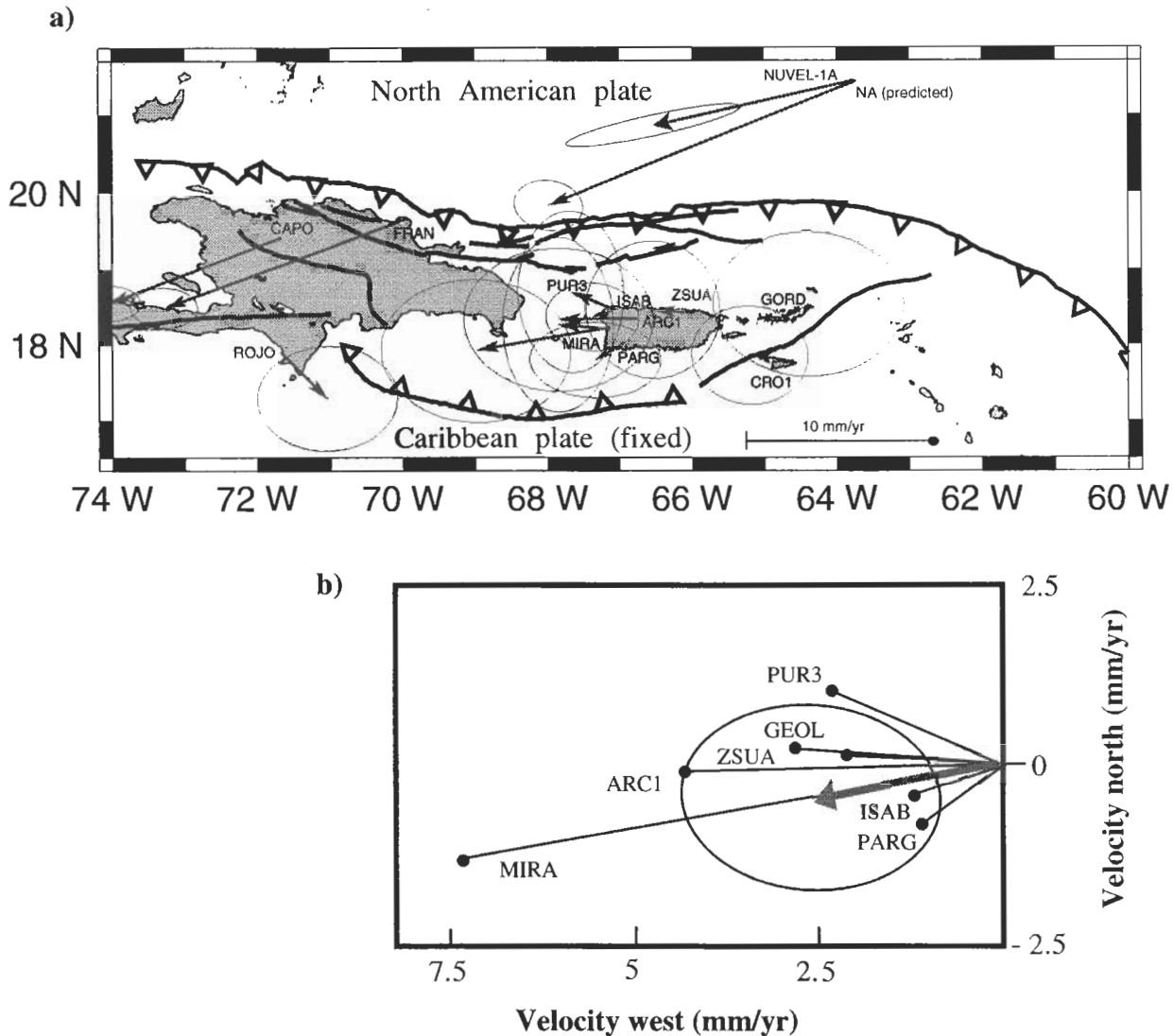
a)

b)

Figure 7. (a) Velocities relative to Caribbean reference frame. Confidence ellipses are 95%. Arrow of predicted North America motion is that predicted using the Caribbean reference frame of *DeMets et al.* [2000]. (b) Velocities of PRVI sites relative to Caribbean plotted at a common origin. Arrow is average PRVI velocity at MIRA derived from Puerto Rico-Caribbean angular velocities and their covariances.

North American plate. The mean velocity of sites in Puerto Rico relative to the Caribbean, computed for western Puerto Rico, is 2.4±1.4 mm/yr toward S79°W±26° (1σ). Individual site velocities (Figure 7) range from 1.4±0.8 mm/yr toward the SW at PARG to 2.5±1.5 mm/yr toward the NW at PUR3 (Figure 7). The velocity of GORD relative to the Caribbean plate is negligible at 0.5±4 mm/yr.

To assess whether the present GPS velocities from sites in Puerto Rico are consistent with significant motion of PRVI relative to the Caribbean plate, we tested for the existence of a separate microplate using the F ratio test of *Stein and Gordon* [1984]. This method compares the least squares fits of models that use two angular velocities and one angular velocity, respectively, to fit a set of kinematic observations. The test is insensitive to systematic overestimates or underestimates of

velocity uncertainties, an important consideration with GPS velocities. Fitting the seven PRVI velocities and four Caribbean GPS velocities with a single angular velocity gives a weighted least squares misfit of 13.0. Fitting the two sets of velocities with separate angular velocities gives a summed misfit of 9.8. The improvement in fit in the latter model, which stems from using three additional adjustable parameters, gives $F = 1.7$, which is significant at only the 80% confidence level for 3 versus 16 (=22-6) degrees of freedom. The test for a separate PRVI microplate thus fails at the 95% confidence level. Although this result is consistent with no current motion of a PRVI block relative to the Caribbean plate, it implies that PRVI bounding faults are inactive. We believe this is unlikely given the existence of significant seismicity along all the boundary structures except the eastern Anegada passage

fault. The interpretation we prefer is that the GPS velocity uncertainties are still too large to detect the predicted 2-3 mm/yr of PRVI block motion relative to the Caribbean at high confidence levels. Assuming that the present estimate of Caribbean plate and PRVI block velocities is correct and the GPS velocity uncertainties decrease progressively through time, numerical experiments suggest that two to three additional years of measurements at the existing sites will be required before the present velocities are sufficiently precise to detect 2.5 mm/yr of PRVI-CA motion at the 95% confidence level.

Velocities in the Dominican Republic relative to the Caribbean are faster and more SSW trending than that of western PRVI (Figure 7a). This difference suggests the existence of separate PRVI and Hispaniola microplates and constrains motion along the bounding structures. Predicted deformation across the Muertos trough is predominantly left-lateral strike slip at the longitude of Puerto Rico with up to 2.3 mm/yr of convergence permissible within error. The Muertos trough is characterized by almost complete convergence near Hispaniola. The kinematics of the Mona rift can be assessed by examining the velocities of western Puerto Rico and those in the eastern Dominican Republic and is discussed below.

7. Geological and Tectonic Implications

7.1 Intrablock Deformation of PRVI

The velocity estimate for sites in Puerto Rico yields errors that are < 2.0 mm/yr, defining the upper bound on permissible deformation within the island. All sites have velocities that are equivalent at the 95% confidence limit. The discrepancy in the velocities between Puerto Rico sites and GORD in Virgin Gorda at the eastern extreme of PRVI is close to the resolution of the current GPS geodetic data, giving relative motion between western (the island of Puerto Rico) and eastern (Virgin Gorda) PRVI at 3±3 mm/yr. Although the scatter of the GPS velocities on PRVI permits several millimeters per year of slip, the absence of any obvious geographic pattern in the velocities leads us to argue against substantial organized deformation within PRVI in favor of deformation slower than the several millimeters per year resolution of the present GPS velocities. We solved for a stronger upper bound on intra-PRVI deformation by examining the evolution of baseline length between the two continuous sites in western Puerto Rico, GEOL and PUR3 (Figure 8). Since continuous measurements began at both stations in June 1997, the baseline length has remained constant within error at -0.5±0.3 mm/yr (1σ). Intrablock deformation therefore is small, and most deformation is likely accommodated along the bounding structures of the microplate.

These data constrain the rigidity of PRVI and bear on the issue of seismic hazard. Specifically, do faults exist within PRVI that are capable of producing locally damaging earthquakes? Shallow microseismicity does occur onshore (Figure 2), but the historic record is consistent with major events confined to the offshore region [McCann and Pennington, 1990]. The highest levels of onshore seismicity are in the southwest corner of Puerto Rico in the Lajas valley [Asencio, 1980], an E-W trending Neogene feature. Faults of similar orientation are mapped offshore south of the Mona rift (Figure 3) [Meltzer, 1997]. The Lajas valley is between our sites at GEOL and PARG, whose velocities agree at 1σ, arguing against significant deformation across the structure. The island of Puerto Rico also is traversed by two major northwest-
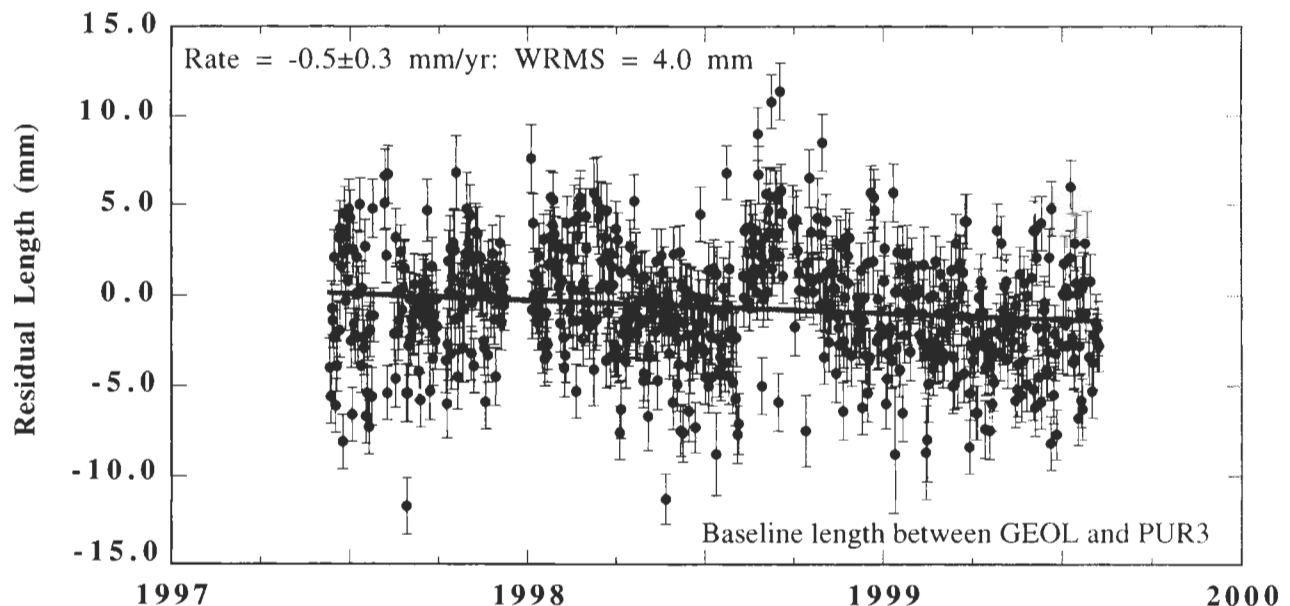

Figure 8. Evolution of residual baseline length between continuous sites PUR3 and GEOL from June 1997. Rate of change of the baseline is -0.5±0.3 mm/yr. Stated error is 1σ formal error without any provision for monument noise. Median baseline length is 28898.713 m. Number of data points is 663.

southeast striking fault zones that were active during the Eocene and are covered by little deformed Neogene strata (Figure 3): (1) the great northern Puerto Rico fault zone (GNPRFZ) and (2) the great southern Puerto Rico fault zone (GSPRFZ). We note that the baseline between the two continuous sites (Figure 8) crosses the GSPRFZ. Elastic strain effects from GSPRFZ on GEOL and PUR3 time series are unlikely. Simple two-dimensional elastic strain models using distances from GSPRFZ of 5 and 25 km for GEOL and PUR3, respectively, a baseline length change between GEOL and PUR3 of 0.5±0.3 mm/yr, and assumed vertical fault orientation with locking depths of 10-20 km suggest the permissible upper bound on GSPRFZ motion is 1.5±2.0 mm/yr. Field evidence for post-Oligocene motion along either the GSPRFZ or GNPRFZ is sparse, which further supports a rigid PRVI since the Miocene.

7.2 Counterclockwise Rotation

Counterclockwise rotation of a rigid PRVI about a vertical axis in southeastern Puerto Rico predicts large lateral linear velocity gradients across the island, extension across the western Puerto Rico trench, and shortening across the Muertos trough south of southwestern Puerto Rico. Velocities of all sites on the island, including ZSUA near San Juan in the east, however, are equivalent within 1σ. Furthermore, the GPS-derived velocity for PRVI is consistent with convergence across the Puerto Rico trench and a significant component of left lateral strike-slip faulting along the Muertos trough south of SW Puerto Rico. On the basis of both observations we argue against significant ongoing rotation about a proximal axis and favor instead northeastward translation of PRVI relative to North America. The geodetic results are supported by focal mechanisms from historic earthquakes, which also yield convergence across the Puerto Rico trench offshore northwestern Puerto Rico [McCann and Pennington, 1990; Deng and Sykes, 1995; Dolan and Wald, 1998]. Offshore seismic profiles were interpreted to document a change from extension to shortening across the Puerto Rico trench in the past few million years [Larue and Ryan, 1998] in agreement with paleomagnetic results from Miocene rocks exposed on Puerto Rico that are consistent with cessation of rotation ~4.5 million years ago [Reid et al., 1991].

7.3 Tectonic Escape of PRVI

Jany et al. [1987] and Mauffret and Jany [1990] suggested that the PRVI block experiences tectonic escape to the east, squeezed like a pumpkin seed between converging Caribbean and North American plates. If correct, this model bears some analogy to the eastward motion of the larger Caribbean plate, which may be driven, at least in part, by the westward increasing convergence between North and South America [Sykes et al., 1982; Dixon and Mao, 1997]. The tectonic escape model makes kinematic predictions that can be tested with our new data. Specifically, it predicts left-lateral strike-slip motion along the northern boundary of the PRVI block and right-lateral motion along the southern boundary. Our new GPS data, however, predict left-lateral motion along both

the northern and southern boundaries. Thus the tectonic escape hypothesis is not compatible with the GPS geodetic data.

This may have more general implications for the kinematic behavior of microplates and blocks in transform plate boundary zones. Our measurements imply a relatively simple, monotonic increase in velocity (i.e., the velocity gradient has a constant sign) along a path from the interior of one bounding plate (e.g., North America) across the PRVI block into the interior of the other (e.g., Caribbean) plate. In contrast, the tectonic escape model, with a mixture of right- and left-lateral strike-slip faults, predicts a velocity gradient that would change sign along a perpendicular traverse from the North American to the Caribbean plate. The simple monotonic increase in velocity that we predict implies that the summed magnitude of strike-slip fault slip rates will equal the total plate motion rate between the Caribbean and North America. In the tectonic escape hypothesis, however, the summed magnitude of slip rates along the same traverse would be higher than the total plate rate. Our preferred model therefore may represent less total energy dissipation compared to the tectonic escape model. Perhaps this is commonly the case for smaller tectonic blocks and microplates, where frictional edge effects, which scale by fault length and slip rate, may be large compared to basal driving forces, which scale by plate area.

7.4 Muertos Trough and Anegada Passage

Assuming that the Puerto Rico block is not rotating significantly relative to the Caribbean plate and that the 2.4±1.4 mm/yr toward S79°W±26° (1σ) of predicted westward motion in central Puerto Rico can be used to describe motion of the PRVI block south of Puerto Rico, displacement along the Muertos trough has a significant left-lateral strike-slip component. Within error, the amount of convergence permissible across the Muertos trough is 2.3 mm/yr. Convergence is greater to the west offshore southeastern Hispaniola, where folds and reverse faults are mapped [Ladd et al., 1977] and GPS velocities relative to the Caribbean are more southerly trending (Figure 7). South of southwestern Puerto Rico the presence of an accretionary complex adjacent to the Muertos trough [Ladd and Watkins, 1978] and seismicity at depths > 100 km [Byrne et al., 1985] favor convergence in this region. Two moderate earthquakes (M = 4.7 and 5) occurred in August 1993 near the eastern termination of the Muertos trough at 65°W where the accretionary prism disappears [Jany et al., 1987; Masson and Scanlon, 1991]. Focal mechanisms generated by the Puerto Rico Seismic Network are consistent with left-lateral strike-slip motion along an E-W striking fault [Huerfano, 1995], corroborating preliminary GPS-derived velocities (Figure 2). E-W striking faults along which predominantly left-lateral slip also is inferred are mapped offshore southwestern Puerto Rico [Meltzer, 1997]. Shortening along the Muertos trough is greatest offshore southwest Puerto Rico and dies out to the east toward the Anegada passage [Masson and Scanlon, 1991].

Assuming that motion along the Muertos trough is conserved and transferred to the western end of the Anegada Passage offshore southeastern Puerto Rico, then displacement

along the western Anegada passage, the Virgin Island and Whiting basins, and/or other structures offshore southeastern Puerto Rico is sinistral transtension of the order of a few millimeters per year (Figure 3). Evidence to support active slip in the region includes high seismicity [*Frankel et al.*, 1980] and the occurrence in 1867 of a large (7 < M < 7.75) tsunamogenic earthquake along the north wall of the Virgin Islands basin that caused extensive damage in St. Croix and St. Thomas [*Reid and Taber*, 1920].

The kinematics of the eastern Anegada passage can be examined by comparing the velocity of St. Croix (CRO1) with that of Virgin Gorda (GORD). Results from GORD must be considered as preliminary since there are only two occupations, albeit separated by 5 years. As discussed above, the velocity at GORD is very similar to that at CRO1, indicating displacement across and along the Anegada Passage in the eastern British Virgin Islands is < 2 mm/yr. The data currently do not distinguish between components of left-lateral and right-lateral strike slip if the existence of strike-slip motion is assumed. *Jany et al.* [1987] argue that dextral motion along the Anegada passage began in the Pliocene and is limited to 6-15 km, implying a displacement rate of 1.5-3.7 mm/yr, which may not be resolvable with GPS geodetic data for several more years. The lack of earthquakes observed along the Anegada passage during deployment of a seismic network in the northern Virgin Islands in the 1970s [*Frankel et al.*, 1980] supports either long recurrence intervals with intervening periods of seismic quiescence or little motion between GORD and CRO1. 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, and ROJO). The westward motion of Puerto Rico relative to GORD in the Caribbean reference frame requires E-W extension between eastern Puerto Rico and the eastern Virgin Islands of a few millimeters per year. The location of structures along which extension north of the Anegada passage may be accommodated are not constrained by the GPS data reported here.

7.5 Mona Rift

The offshore deformation between Hispaniola and Puerto Rico reflects relative motions of eastern Hispaniola with respect to western PRVI. The opening rate for the Mona rift can be estimated from comparison of the average GPS-derived velocity for Puerto Rico with those of the northern Dominican Republic. The calculated extension depends on the amount of elastic strain accumulation on active faults in the Dominican Republic and the errors associated with the GPS-derived velocities.

The two major E-W to WNW trending fault zones traversing the island of Hispaniola, the Septentrional fault zone in the north and the Enriquillo fault zone in the south (Figure 1), have present-day slip rates in excess of several millimeters per year as estimated from geologic evidence [*Prentice et al.*, 1993; *Mann et al.*, 1998]. Some deformation also likely occurs immediately offshore to the north of Hispaniola along the

north Hispaniola deformed belt, a submarine zone of folds and thrusts, which was the locus of a series of large thrust earthquakes in 1946 and 1948 [*Russo and Villaseñor*, 1995; *Dolan and Wald*, 1998].

Two-dimensional elastic modeling of strain accumulation across Hispaniola, using GPS-derived velocities from three sites in the Dominican Republic and one site in Grand Turk, seismogenic depths of 15-20 km, and imposed vertical fault geometries, yields fault-parallel slip estimates along the north Hispaniola deformed belt and the Septentrional fault of 4±3 mm/yr and 8±3 mm/yr, respectively [*Dixon et al.*, 1998]. Geologically derived Holocene rates yield maximum slip estimates along distinct segments of the Septentrional fault of 13±4 mm/yr and 23±6 mm/yr [*Mann et al.*, 1998].

Although the GPS velocities are preliminary because the geodetic data set is spatially limited, they do provide some constraints on the kinematics of the Mona rift. The eastward projections of both the north Hispaniola deformed belt and the Septentrional fault lie offshore northern Puerto Rico. If we assume that the displacement along the north Hispaniola deformed belt and the Septentrional fault is representative of slip offshore northern Puerto Rico, the GPS-derived velocity for Puerto Rico with respect to North America should reflect the integrated slip along offshore structures and the displacement associated with the Mona rift. The GPS-derived average velocity for Puerto Rico with respect to North America is 16.9±1.1 mm/yr toward N68°E±3° (1σ). The integrated slip along the north Hispaniola deformed belt and the Septentrional fault estimated from 2-D elastic modeling of strain accumulation is 12±4 mm/yr toward the ENE. Thus western Puerto Rico moves eastward relative to central Hispaniola south of the Septentrional fault at an estimated velocity of 5±4 mm/yr. This rate is the upper bound on the opening rate of the N-S trending Mona rift offshore northwestern Puerto Rico, requiring that all the eastward motion is accommodated across this structure. (A small northward component of motion of Puerto Rico relative to central Hispaniola also is possible, which would impart minor left-lateral slip along the N-S trending bounding faults of the Mona rift.)

The total extension across the Mona rift constrained by seismic profiles is ~6 km [*van Gestel et al.*, 1998]. Using an opening rate of 5 mm/yr estimated from GPS velocities yields a minimum age of the structure of 1.2 million years, confirming the youth of the Mona rift and postdating the 4.5 million year age for the end of PRVI counterclockwise rotation inferred from paleomagnetic data [*Reid et al.*, 1991]. The minimum and maximum ages of the Mona rift, within the errors of the GPS data, are < 1 million and 6 million years, respectively.

The GPS velocities from the northeastern Caribbean permit us to estimate preliminary displacements along the major bounding structures of the PRVI block. We argue that at least one, and possibly two, extensional belts occur between Hispaniola and the eastern Virgin Islands along which slip is transferred from the southern limit of the North America-Caribbean plate boundary zone to the northern portion. The first and more significant is the Mona rift across which extension is captured by our GPS data. The second potential belt is the area between eastern Puerto Rico and the Virgin Islands, which may experience minor extension in response to differential motion between eastern Puerto Rico (ZSUA) and Virgin

Gorda (GORD) that remains unresolved within current uncertainties. PRVI behaves rigidly between these two extensional zones. The N-S trending Mona rift accommodates ~5 mm/yr of east-west opening, which results in a reduction of slip along the southern plate boundary zone from ~8 mm/yr along the Enriquillo fault, estimated from 2-D modeling of GPS data acquired between 1986 and 1995 in Hispaniola [*Dixon et al.* 1998], to ~3 mm/yr along the Muertos trough. East of Puerto Rico an additional ~2 mm/yr must transfer from the western Anegada passage northward to the eastern Puerto Rico trench to allow for little or no motion between GORD and CRO1. The increased seismicity and focal mechanisms north of the northeastern Virgin Islands are consistent with this interpretation (Figure 2).

8. Conclusions

We document the existence of a distinct PRVI block within the diffuse boundary zone between the North American and Caribbean plates from GPS geodetic data collected in Puerto Rico, the Virgin Islands, and eastern Hispaniola. At the 95% confidence level, GPS velocities for sites in PRVI are equivalent, with the exception of one site (GORD) in the eastern British Virgin Islands. Intrablock displacement therefore is less than a few millimeters per year and deformation associated with North American-Caribbean relative plate motion is limited to the block-bounding structures. The velocity of the

eastern British Virgin Islands (GORD) closely approximates that of St. Croix (CRO1) on the rigid Caribbean plate. We infer that PRVI is attached to the Caribbean at its eastern edge. Motion of PRVI relative to North America is slower than that between the rigid Caribbean and North American plates, precluding eastward tectonic escape of PRVI within the plate boundary zone.

GPS velocities predict left-lateral transpression across the Puerto Rico trench and the Muertos trough south of Puerto Rico, left-lateral transtension across the western Anegada passage, and east-west opening across the Mona rift. This deformation pattern is not compatible with rotation of a rigid PRVI about a vertical axis located in the southeast of the island of Puerto Rico but is consistent with northeastward translation of PRVI relative to North America and eastern Hispaniola.

References

Argus, D. F., and R. G. Gordon, Tests of the rigid-plate hypothesis and bounds on intraplate deformation using geodetic data from very long baseline interferometry, *J. Geophys. Res.*, *101*, 13,555-13,572, 1996.

Asencio, E., Western Puerto Rico seismicity, *U.S.Geol.Surv. Open File Rep. 80-192*, 135 pp., 1980.

Blewitt, G., M. B. Heflin, F. H. Webb, U. J. Lindqwister, and R. P. Malla, Global coordinates with centimeter accuracy in the International Terrestrial Reference Frame using GPS, *Geophys. Res. Lett.*, *19*, 853-856, 1992.

Burke, K., J. Fox, and A. M. Celal Sengor, Bouyant ocean floor and the evolution of the Caribbean, *J. Geophys. Res.*, *83*, 3949-3954, 1978.

Byrne, D. B., G. Suarez, and W. R. McCann, Muertos Trough subduction--Microplate tectonics in the northern Caribbean?, *Nature, 317*, 420-421, 1985.

Calais, E., and B. Mercier de Lepinay, Semiquantitative modeling of strain and kinematics along the Caribbean/North America strike-slip plate boundary zone, *J. Geophys. Res.*, *98*, 8293-8308, 1993.

Conolly, J. R., and M. Ewing, Sedimentation in the Puerto Rico Trench, *J. Sediment. Petrol., 37*, 44-59, 1967.

DeMets, C., and T. Dixon, New kinematic models for Pacific-North America motion from 3 Ma to present, 1, Evidence for steady motion and biases in the NUVEL-1A model, *Geophys. Res. Lett.*, *26*, 1921-1924, 1999.

DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein, Current plate motions, *Geophys. J. Int.*, *101*, 425-478, 1990.

DeMets, C., P. Jansma, G. Mattioli, T. Dixon, F. Farina, R. Bilham, E. Calais, and P. Mann, GPS geodetic constraints on Caribbean-

North America plate motion: Implications for plate rigidity and oblique plate boundary convergence, *Geophys. Res. Lett.*, *27*, 437-440, 2000.

Deng, J., and L. R. Sykes, Determination of Euler pole for contemporary relative motion of Caribbean and North American plates using slip vectors of interplate earthquakes, *Tectonics, 14*, 39-53, 1995.

Dixon, T. H., and A. Mao, A GPS estimate of relative motion between North and South America, *Geophys. Res. Lett.*, *24*, 535-538, 1997.

Dixon, T., G. Gonzales, E. Katsigris, and S. Lichten, First epoch geodetic measurements with the Global Positioning System across the northern Caribbean plate boundary zone, *J. Geophys. Res.*, *96*, 2397-2415, 1991.

Dixon, T. H., A. Mao, and S. Stein, How rigid is the stable interior of the North American Plate?, *Geophys. Res. Lett.*, *23*, 3035-3038, 1996.

Dixon, T. H., F. Farina, C. DeMets, P. Jansma, P. Mann, and E. Calais, Caribbean-North American plate relative motion and strain partitioning across the northern Caribbean plate boundary zone from a decade of GPS observations, *J. Geophys. Res.*, *103*, 15,157-15,182, 1998.

Dixon, T. H., M. Miller, F. Farina, H. Wang, and D. Johnson, Present-day motion of the Sierra Nevada block and some tectonic implications for the Basin and Range province, North American Cordillera, *Tectonics, 19*, 1-24, 2000.

Dolan, J. F., and D. J. Wald, The 1943-1953 north-central Caribbean earthquakes: active tectonic setting, seismic hazards and implications for Caribbean-North American plate motions, in *Active strike-slip and collisional tectonics of the northern Caribbean*

Plate boundary zone, edited by J. Dolan, and P. Mann, *Spec. Pap. Geol. Soc. Am. Spec. Paper , 326*, 143-161, 1998.

Dolan, J., H. Mullins, and D. Wald, Active tectonics of the north-central Caribbean: oblique collision, strain partitioning, and opposing subducted slabs, in *Active strike-slip and collisional tectonics of the northern Caribbean Plate boundary zone*, edited by J. Dolan, and P. Mann, *Spec. Pap. Geol. Soc. Am., 326*, 1-61, 1998.

Donelly, T. W., Evolution of eastern Greater Antillean island arc, *Am. Assoc. Pet. Geol. Bull., 48*, 680-696, 1964.

Ewing, M., A. G. Lonardi, and J. I. Ewing, The sediments and topography of the Puerto Rico Trench and outer ridge, *Trans. Caribb. Geol. Conf., 4, 325-334, 1965.

Fink, L. K., Jr., and C. G. A. Harrison, Paleomagnetic investigations of selected lava units on Puerto Rico, *Trans. Caribb. Geol. Conf., 6*, 379, 1972.

Frankel, A., A composite focal mechanism for microearthquakes along the northeastern border of the Caribbean plate, *Geophys. Res. Lett., 9*, 511-514, 1982.

Frankel, A., W. R. McCann, and A. J. Murphy, Observations from a seismic network in the Virgin Islands region: Tectonic structures and earthquake swarms, *J. Geophys. Res., 85*, 2669-2678, 1980.

Grindlay, N. R., P. Mann, and J. F. Dolan, Researchers investigate submarine faults north of Puerto Rico, *EOS Trans. AGU, 78 (38)*, 404, 1997.

Heflin, M., et al., Global geodesy using GPS without fiducial sites, *Geophys. Res. Lett., 19*, 131-134, 1992.

Hess, H. H., and J. C. Maxwell, Caribbean research project, *Geol. Soc. Am. Bull., 64*, 1-6, 1953.

Holcombe, T. L., C. G. Fisher, and F. A. Bowles, Gravity-flow deposits from the St. Croix Ridge: Depositional history, *Geo Mar. Lett.*, 9, 11-18, 1989.

Huerfano, V., Crustal structure and stress regime near Puerto Rico, M.S. thesis, Univ. of Puerto Rico, Mayagüez, 1995.

Jany, I., A. Mauffret, P. Bouysse, A. Mascle, B. Mercier de Lépinay, V. Renard, and J. F. Stephan, Relevé bathymétrique Sea beam et tectonique en décrochement au sud des Iles Vierges [Nord-Est Caraibes], *C. R. Acad. Sci., Ser. II*, 304, 527-532, 1987.

Ladd, J. W., and J. S. Watkins, Active margin structures within the north slope of the Muertos Trough, *Geol. Mijnbouw*, 57, 225-260, 1978.

Ladd, J. W., J. L. Worzel, and J. S. Watkins, Multifold seismic reflection records from the northern Venezuela Basin and the north slope of Muertos Trench, in, *Maurice Ewing Ser., Island Arcs, Deep-Sea Trenches and Back-Arc Basins*, vol. 1, edited by M. Talwani and W. C. Pitman, pp. 41-56, AGU, Washington, D. C. 1977.

Larue, D. K., and H. F. Ryan, Extensional tectonism in the Mona Passage, Puerto Rico and Hispaniola: a preliminary study: *Trans. Caribb. Geol. Conf.*, 12, 301-313, 1990.

Larue, D. K., and H. F. Ryan, Seismic reflection profiles of the Puerto Rico Trench; shortening between the North American and Caribbean plates, in, *Tectonics and geochemistry of the northeastern Caribbean*, edited by E. G. Lidiak and D. K. Larue, *Spec. Pap. Geol. Soc. Am.*, 322, 193-210, 1998.

Larue, D. K., J. Joyce, and H. F. Ryan, Neotectonics of the Puerto Rico Trench; extensional tectonism and forearc subsidence, *Trans. Caribb. Geol. Conf.*, 12, 231-247, 1990.

Leroy, S., and A. Mauffret, Intraplate deformation in the Caribbean region, *J. Geodyn.*, 21, 113-122, 1996.

Lichten, S. M., Estimation and filtering for high precision GPS applications, *Manuscr. Geod.*, 15, 159-176, 1990.

Malfait, B., and M. B. Dinkelman, Circum-Caribbean tectonic and igneous activity and the evolution of the Caribbean plate, *Geol. Soc. Am. Bull.*, 83, 251-272, 1972.

Mann, P., and K. Burke, Neotectonics of the Caribbean, *Rev. Geophys.*, 22, 309-362, 1984.

Mann, P., C. Schubert, and K. Burke, Review of Caribbean neotectonics, in *The Geology of North America*, vol. H, *The Caribbean Region*, edited by G. Dengo and J. E. Case, pp. 307-308, Geol. Soc. Am., Boulder, Colo., 1990.

Mann, P., F. Taylor, L. Edwards, and T. Ku, Actively evolving microplate formation by oblique collision and sideways motion along strike-slip faults: An example from the northeastern Caribbean plate margin, *Tectonophysics*, 246, 1-69, 1995.

Mann, P., C. S. Prentice, G. Burr, L. R. Pena, and F. W. Taylor, Tectonic geomorphology and paleoseismicity of the Septentrional fault system, Dominican Republic, in *Active strike-slip and collisional tectonics of the northern Caribbean Plate boundary zone*, edited by J. Dolan, and P. Mann, *Spec. Pap. Geol. Soc. Am.*, 326, 63-124, 1998.

Mao, A., C. G. A. Harrison, and T. H. Dixon, Noise in GPS coordinate time series, *J. Geophys. Res.*, 104, 2797-2816, 1999.

Masson, D. G., and K. M. Scanlon, The neotectonic setting of Puerto Rico, *Geol. Soc. Am. Bull.*, 103, 144-154, 1991.

Matthews, J., and J. Holcombe, Possible Caribbean underthrusting of the Greater Antilles along the Muertos Trough, *Trans. Caribb. Geol. Conf.*, 7, 235-242, 1976.

Mauffret, A., and I. Jany, Collision et tectonique d'expulsion le long de la frontiere Nord-Caraibe, *Oceanol. Acta*, 10, 97-116, 1990.

McCann, W. R., On the earthquake hazards of Puerto Rico and the Virgin Islands, *Bull. Seismol. Soc. Am.*, 75, 251-262, 1985.

McCann, W. R., and W. D. Pennington, Seismicity, large earthquakes, and the margin of the Caribbean plate, in, *The Geology of North America*, vol. H, *The Caribbean Region*, edited by G. Dengo and J. Case, pp. 291-306, Geol. Soc. Am., Boulder, Colo., 1990.

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.

Meltzer, A. S., Fault structure and earthquake potential, Lajas Valley, SW Puerto Rico, *U. S. Geol. Surv. Rep.*, 16 pp., 1997.

Mercado, A., and W. McCann, Numerical simulation of the 1918 Puerto Rico tsunami, *J. Nat. Hazards*, 18, 57-76, 1998.

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

Moussa, M. T., G. Seiglie, A. A. Meyerhoff, and I. Taner, The Quebradillas Limestone [Miocene-Pliocene], northern Puerto Rico, and tectonics of the northeastern Caribbean margin, *Geol. Soc. Am. Bull.*, 99, 427-439, 1987.

Murphy, A. J., and W. R. McCann, Preliminary results from a new seismic network in the northeastern Caribbean, *Seismol. Soc. Am. Bull.*, 69, 1497-1513, 1979.

Muszala, S. P., N. Grindlay, and R. T. Bird, Three-dimensional Euler deconvolution and tectonic interpretation of marine magnetic anomaly data in the Puerto Rico trench, *J. Geophys. Res.*, 104, 29,175-29,188, 1999.

Nemec, M. C., A two-phase model for the tectonic evolution of the Caribbean, *Trans. Caribb. Geol. Conf.*, 9, 23-34, 1980.

Officer, C. B., Jr., R. S. Edwards, J. I. Ewing, and H. R. Johnson, Geophysical investigations in the eastern Caribbean: Venezuelan Basin, Antilles Island Arc, and Puerto Rico trench, *Geol. Soc. Am. Bull.*, 68, 359-378, 1957.

Pacheco, J. F., and L. R. Sykes, Seismic moment catalog of large shallow earthquakes, 1900 to 1989, *Bull. Seismol. Soc. Am.*, 82, 1306-1349, 1992.

Prentice, C., P. Mann, F. W. Taylor, G. Burr, and S. Valastro, Paleoseismicity of the North American plate boundary [Septentrional Fault], Dominican Republic, *Geology*, 21, 49-52, 1993.

Reid, H., and S. Taber, The Virgin Islands earthquakes of 1867-1868, *Bull. Seismol. Soc. Am.*, 10, 9-30, 1920.

Reid, J., P. Plumley, and J. Schellekens, Paleomagnetic evidence for late Miocene counterclockwise rotation of the North Coast carbonate sequence, Puerto Rico, *Geophys. Res. Lett.*, 18, 565-568, 1991.

Rosencrantz, E., and P. Mann, SeaMARC II mapping of transform faults in the Cayman Trough, Caribbean Sea, *Geology*, 19, 690-693, 1991.

Russo, R. M., and A. Villaseñor, The 1946 Hispaniola earthquake and the tectonics of the North America-Caribbean plate boundary zone, northeastern Hispaniola, *J. Geophys. Research*, 100, 6265-6280, 1995.

Sillard, P., Z. Altamimi, and C. Boucher, The ITRF-96 realization and its associated velocity field, *Geophys. Res. Lett.*, 25, 3222-3226, 1998.

Speed, R. C., and D. K. Laruc, Extension and transtension in the plate boundary zone of the northeastern Caribbean, *Geophys. Res. Lett.*, 18, 573-576, 1991.

Stein, S., and R. G. Gordon, Statistical tests of additional plate boundaries from plate motion, *Earth Planet. Sci. Lett.*, 69, 401-412, 1984.

Stein, S., C. DeMets, R. G. Gordon, J. Brodholt, D. Argus, J. F. Engeln, P. Lundgren, C. Stein, D. S. Weins, and D. F. Woods, A test of alternative Caribbean plate relative motion models, *J. Geophys. Res.*, 93, 3041-3050, 1988.

Sykes, L. R., W. R. McCann, and A. L. Kafka, Motion of Caribbean plate during last 7 million years and implications for earlier Cenozoic movements, *J. Geophys. Res.*, 87, 10,656-10,676, 1982.

Van Fossen, M. C., J. T. Channel, and J. H. Schellekens, Paleomagnetic evidence for Tertiary anticlockwise rotation in southwest Puerto Rico, *Geophys. Res. Lett.*, 16, 819-822, 1989.

van Gestel, J., P. Mann, J. Dolan, and N. Grindlay, Structure and tectonics of the upper Cenozoic Puerto Rico-Virgin Islands carbonate platform as determined from seismic reflection studies, *J. Geophys. Res.*, 103, 30,505-30,530, 1998.

Ward, S. N., Pacific-North America plate motions: new results from very long baseline interferometry, *J. Geophys. Res.*, 95, 21965-21981, 1990.

Zumberge, J. F., M. Heflin, D. Jefferson, M. Watkins, and F. Webb, Precise point positioning for efficient and robust analysis of GPS data from large networks, *J. Geophys. Res.*, 102, 5005-5017, 1997.

E. Calais, Géosciences Azur, Centre National de Recherches Scientifique, 06560 Valbonne, France.

C. DeMets, Department of Geology and Geophysics, University of Wisconsin, Madison, WI 53706.

T. H. Dixon, Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, Miami, FL 33149.

P. E. Jansma, Department of Geosciences, University of Arkansas, Fayetteville, AR 72701.

P. Mann, Institute for Geophysics, University of Texas at Austin, Austin, TX 78759-8500.

G. S. Mattioli and A. Lopez, Department of Geology, University of Puerto Rico, P.O. Box 9017, Mayagüez, PR 00681-9017.

(p_jansma@comp.uark.edu; glen@geology.uprm.edu)