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

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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 Greater Antilles, (2) the Hispaniola, and (3) the Puerto Rico–northeastern 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 displacement 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 36.4°/yr toward N68°E, 2°/yr toward 578°W, 26°/yr (10), respectively. In contrast with some recent models, ongoing rotation of PRVI about a nearly vertical (c. 25°) axis is not supported by the geodetic data. In addition, we argue against eastward tecotonic 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 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 south of Puerto Rico. Differences in GPS-derived velocities from Hispaniola and PRVI yield east-west extension across the N-S trending 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; Mora 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–northeastern 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 SW and SE orientated faults, which form the E-W trending Cayman trough and bound the short (~100 km) N-S trending Mona 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 Greater Antilles [Mora et al., 1995], (2) the Hispaniola [Byrne et al., 1985], and (3) the Puerto Rico–northeastern Virgin Islands (PRVI) [Hassan 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 Orient, Southeastern, Enriquillo–Platynau Gardens, and Arecibo faults, the Muertos trough and North Hispaniola deformed belt, and the Mona rift faults northwest of Puerto Rico (Figure 1). Both rotation about a nearly vertical axis [Mora et al., 1995] and tecotonic escape to the east [Jary et al., 1987] have been proposed for PRVI. A rigorous test of the
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., Weiss 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 [Dren and others, 1991, 1998], and by the development of a Caribbean plate reference frame from GPS geodetic measurements in the Caribbean interior [DeMets and others, 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 nearly (-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. Relativ 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 and others, 1990] to 37±5 mm/yr to the northeast as derived from earthquake slip vectors [Sykes and others, 1982; Dong 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±4.1 mm/yr toward N89°E3° (1σ) [Ries and others, 1998]. Incorporation of additional unpublished data from our 1998 observations decreases the rate slightly to 19.4±2.2 mm/yr and yields a revised azimuth toward N79°E3° (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 undetected deformation in the offshore farther south [Harvey and Mansfield, 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 and others, 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 [Dong and Sykes, 1995] and GPS data [DeMets and others, 2000] are consistent with some transpression east of Coiba. 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 and others, 1982; Frankel, 1982; Mann and Burke, 1984, Byrne and others, 1985; Stein and others, 1988; Mann and others, 1990; Bonnet and Mann, 1991; Colais and Mercier de Lagnies, 1993; Dong and Sykes, 1995]. The convergence implied by these features, however, may record local block tectonics within the broad, deforming

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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. Dong and Sykes [1995], and Molnar and Sykes [1990]. They 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; NPIFS, north Puerto Rico slope fault; PRT: Puerto Rico trench; SF: SARMAN fault; SPSRF, south Puerto Rico slope fault; YR: Yoma rift.
plate boundary rather than relative motion of the rigid Caribbem 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, [Dissanayake 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 1918, 1928, 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 (Ms = 7.5) and the 1670 San Cristobal earthquake (Ms = 6.5) [Gabash and Sykes, 1992]. With most events concentrically oriented, 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 Scarson, 1991].

The north side of PRVI is bounded by the east-west striking Puerto Rico trench, which has ~300 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 two-angle theories imaged in seismic profiles of the western Puerto Rico trench [Sykes et al., 1982; McCann, 1985; Deng and Sykes, 1995; Larson and Ryan, 1998]. In contrast, Speed and Lorre [1991] and Masson and Scarson [1991] inferred extension across the trench offshore southwestern Puerto Rico from evidence of subidence since the Pliocene of the northern insular shelf of Puerto Rico implied by Miocene shallow water fanstones in water depths of 5000 m [Masson et al., 1987]. Although our previous GPS-derived velocities [Dissanayake 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 divergence or divergence across the structure. The Puerto Rico system 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 (SPRF), however, also may take up some displacement [Gribbly et al., 1997].

The Muertos trough, an east-west striking bathymetric feature of ~3.5 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; Larson and Ryan, 1990; McCann and Pennington, 1990; Masson and Scarson, 1991; Deng and Sykes, 1995]. Along PRVI, ongoing subduction of Caribbean lithosphere is less clear. Indeed, Sibuet and Dibellema [1972] and Barre et al. [1978] argued that subduction ended in the Oligocene. Subsequent seismic images show that the accretionary prism narrows outward and disappears near 65°W, southwest of St. Croix [Houffer and Jones, 1990; Masson and Scarson, 1991], but a zone of 40 km of underthrusting is present 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 Puerto Rico trench [Masson and Scarson, 1991].

To the west, PRVI is separated from Hispaniola by the Mona Passage (Figure 2). Studies of seafloor structure [Loure and Ryan, 1990; 1998; van Geetel 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 northwest Puerto Rico. A significant earthquake in 1918 (Ms = 7.3) in this area was accompanied by 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 [Merricks and McConv, 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. Tectonic mechanisms of some more recent events offshore northwestern Puerto Rico are consistent with normal faulting along N-S striking planes (Figure 2). The nature of the potential 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] [Lany et al., 1987; Grimaldy et al., 1997], but the kinematics of the structure are not well constrained. Surface ruptures along the continuity of the Muertos trough from southeastern Hispaniola to southwestern Puerto Rico [Lany et al., 1987].

Eastern PRVI is bounded by the N-S trending Anegada passage (Figure 2), which connects the Neognate Virgin Island and Whiting basins in the southwest (Figures 1 and 3) with the Southern Basin and the zone of probable transgression along which displacement from the eastern end of the Muertos trough is transferred to the Puerto Rico trench [Lany et al., 1987; Masson and Scarson, 1991]. Both right-lateral [Vonon, 1980; Mathews and Holcombe, 1976; Lany et al., 1987] and left-lateral strike-slip components of motion have been proposed for the Anegada passage fault [Hess and Massell, 1953; Donnelly, 1964]. Differential 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 McConv, 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., 1990]. 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
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 [Jory et al., 1987, Holcombe et al., 1989, Jory et al., 1987, Masson and Scanlon, 1991] requiring extension across the structure [Speed and Larson, 1991]. Throats 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 Miocene (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 Larson and Ryan [1998] and van Geel 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 contractual across the entire E-W
trending Puerto Rico trench, including the western segment offshore southwestern 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. Mannfred 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; Guanatillo (GTM0), Cuba; Cabo Rojo (ROJ0), Capitillo (CAP0), and Cabo Frances Viejo (FVJ0) in the Dominican Republic, St. Croix (STX0), U.S. Virgin Islands, and Isabella (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, STX0, 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 GORDO) plus campaign sites MIRA (Mirena-Magaguad), ZSUA (San Juan), MONA (Mona Island), DSCH (Descheou Island), ADU (Adjudants), ARCI (Arcelle), CM55 (Ponce), FAJA (Juyano), LAJ1, LAJ2, and LAJ3 (Lajas Valley), and ANEG (Anegada, British Virgin Islands) and continuous sites GEOL in Mayagüez and FAJA in Aguadilla operated by the Department of Geology, University of Puerto Rico, and PURJ in Aguadilla maintained by the U.S. Coast Guard.

GPS campaign data were collected using two different receiver/processor 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 SStx antenna with ground plane. All observations after June 1996, with the exception of the 1998 campaigns at SANA and AVES, were obtained with Trimble 4000 SSe 12-channel, dual-frequency, code phase receivers equipped with Trimble Dom-Magasin type choke ring antennae. Data were collected and archived at a 30 s epoch using a 10th elevation mask. A minimum of 48 hours of good 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 used during data acquisition. The University of Puerto Rico, Systemantics (UPRM) (GEOL, and FAJA), National Oceanographic and Atmospheric Administration (NOAA) (PURJ), and R5 (CRO1) continuous stations

all have choke ring antennae and record at 30 s rate to 5th
elevation. GEOL, FAJA, and PURJ use Trimble 4000S receiver,
while the CRO1 site is equipped with an AOA Turbo Rogue receiver.

Data from continuous sites PURJ, GEOL, and CRO1 (Figure 4) and campaign sites ISAB, PARG, MIRA, ARCI, ZSUA, and GORDO (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, Mayaguez, 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 nonfundamental 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 [Stillard et al., 1998] (Table 1) [e.g., Blewitt et al., 1992; Hehn et al., 1992]. Errors shown for daily site positions are scaled for errors. Velocity estimates use a weighted least squares fit to daily site positions. Uncertainty on derived velocities is inferred from uncertainty in the method 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 ARCI, GEOL, ISAB, MIRA, PARG, PURJ, and ZSUA to find the weighted least squares best fit angular velocities for the seven sites. The average rate misfit of the 13 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, GEO1, 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 PRV1 campaign sites: ISAB, MIRA, PARG, ARC1, ZSU/A, and GORD. Point positions are in ITRF96. Solution errors are scaled by formal errors from GPS interferometric positioning system, orbit analysis, and simulation software package (GIPSY-OASIS III).
Figure 5. (continued)

Table 1. Velocities of PRVI Sites and CROI in ITRF96a

<table>
<thead>
<tr>
<th>Site</th>
<th>Velocity North (ITRF96) mm/yr</th>
<th>Velocity East (ITRF96) mm/yr</th>
<th>Latitude, N</th>
<th>Longitude, E</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARC1</td>
<td>11.9 ± 2.5</td>
<td>6.6 ± 3.3</td>
<td>18.35</td>
<td>293.25</td>
</tr>
<tr>
<td>CROI</td>
<td>13.5 ± 1.5</td>
<td>9.0 ± 1.8</td>
<td>17.76</td>
<td>295.42</td>
</tr>
<tr>
<td>GEOL</td>
<td>12.0 ± 3.1</td>
<td>8.2 ± 1.7</td>
<td>18.21</td>
<td>292.86</td>
</tr>
<tr>
<td>GORD</td>
<td>13.6 ± 2.5</td>
<td>11.3 ± 3.3</td>
<td>18.43</td>
<td>295.56</td>
</tr>
<tr>
<td>ISAB</td>
<td>11.4 ± 0.9</td>
<td>9.6 ± 1.3</td>
<td>18.87</td>
<td>292.95</td>
</tr>
<tr>
<td>MIRA</td>
<td>10.5 ± 2.5</td>
<td>3.6 ± 3.3</td>
<td>18.23</td>
<td>292.87</td>
</tr>
<tr>
<td>PARG</td>
<td>11.1 ± 1.1</td>
<td>10.0 ± 2.1</td>
<td>17.97</td>
<td>292.96</td>
</tr>
<tr>
<td>PUR3</td>
<td>12.8 ± 0.8</td>
<td>8.5 ± 1.6</td>
<td>18.43</td>
<td>292.93</td>
</tr>
<tr>
<td>ZSUA</td>
<td>12.5 ± 2.4</td>
<td>8.8 ± 2.2</td>
<td>18.43</td>
<td>294.01</td>
</tr>
</tbody>
</table>

a Uncertainties are 1 standard error.
the PRVI plate 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 American 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 36 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 169°E (16).
Table 2. Velocities of PRVI Sites and CROI With Respect to Stable North America

<table>
<thead>
<tr>
<th>Site</th>
<th>Velocity North, mm/yr</th>
<th>Velocity East, mm/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARCI</td>
<td>6.9 ± 2.6</td>
<td>13.5 ± 2.4</td>
</tr>
<tr>
<td>CROI</td>
<td>7.7 ± 1.6</td>
<td>15.7 ± 7.0</td>
</tr>
<tr>
<td>GEOR</td>
<td>7.1 ± 5.1</td>
<td>15.1 ± 19.0</td>
</tr>
<tr>
<td>GORD</td>
<td>7.8 ± 2.6</td>
<td>18.2 ± 3.4</td>
</tr>
<tr>
<td>ISAS</td>
<td>6.5 ± 1.1</td>
<td>16.6 ± 1.5</td>
</tr>
<tr>
<td>MIRA</td>
<td>5.8 ± 2.6</td>
<td>10.4 ± 3.4</td>
</tr>
<tr>
<td>PARH</td>
<td>6.2 ± 1.2</td>
<td>16.8 ± 2.8</td>
</tr>
<tr>
<td>PURH</td>
<td>7.9 ± 2.9</td>
<td>15.5 ± 1.8</td>
</tr>
<tr>
<td>ZSU A</td>
<td>7.2 ± 2.4</td>
<td>15.7 ± 2.4</td>
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</table>

* 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 relative 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 N69°E±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. Motion 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 nemezu 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 [Zeng and Sykes, 1995] and to the SPSRF [Gribble et al., 1997]. SPSRF is predominantly strike slip, whereas the Main ridge is a compressional feature oriented perpendicular to the PRVI-North America relative motion vector [Mazzulla 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 N75°E±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 N66°E±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 two, relative to North America at GORD and PRVI is barely above the 2 mm/yr level of the noise associated with GPS geometric 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 breach exists between GORD and eastern Puerto Rico. If the motion at GORD does prove to be the same as at CROI 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 Anguilla 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 Sumbareh trend north of the northeastern Virgin Islands (Figure 2), where an earthquake swarm occurred in the late 1970s [Fram 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 TPR96 come from ROHO in the southern Dominican Republic. SANA on San Andres Island in the western Caribbean, AVIS on Avie Island in the eastern Caribbean, and CROI on St. Croix (Figure 1). Our results do not change significantly if the CROI velocity is eliminated from the angular velocity solution. Details of the interplate 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 CROI With Respect to Stable Caribbean

<table>
<thead>
<tr>
<th>Site</th>
<th>Velocity North, mm/yr</th>
<th>Velocity East, mm/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARCI</td>
<td>4.1 ± 2.7</td>
<td>-4.3 ± 3.5</td>
</tr>
<tr>
<td>CROI</td>
<td>0.4 ± 2.0</td>
<td>-2.4 ± 2.2</td>
</tr>
<tr>
<td>GEOR</td>
<td>0.2 ± 3.2</td>
<td>2.8 ± 2.1</td>
</tr>
<tr>
<td>GORD</td>
<td>0.5 ± 2.8</td>
<td>0.3 ± 3.5</td>
</tr>
<tr>
<td>ISAS</td>
<td>-0.4 ± 1.4</td>
<td>-1.2 ± 3.8</td>
</tr>
<tr>
<td>MIRA</td>
<td>-1.3 ± 2.7</td>
<td>-7.4 ± 3.5</td>
</tr>
<tr>
<td>PARH</td>
<td>-0.8 ± 1.5</td>
<td>-1.1 ± 2.4</td>
</tr>
<tr>
<td>PURH</td>
<td>1.0 ± 3.0</td>
<td>-2.3 ± 2.0</td>
</tr>
<tr>
<td>ZSU A</td>
<td>0.1 ± 2.6</td>
<td>-2.1 ± 2.5</td>
</tr>
</tbody>
</table>

* Uncertainties are 1 standard error. Velocities and errors are based on values in Table 1.
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 7°7'W,620° (1σ). Individual site velocities (Figure 7) range from 1.4±0.8 mm/yr toward the SW at PARQ 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 Stern and Gordaon [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 fit of 13.0. Fitting the two sets of velocities with separate angular velocities gives a summed fit of 9.8. The improvement in fit to 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 ($\approx 22.6$) 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 Anguilla 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 finer 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 latitude 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 Intra-block 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 extremity 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 3.4 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). Intra-block 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 [Alencio, 1981], an E-W trending Neogene feature. Faults of similar orientation are mapped offshore south of the Mona rift (Figure 3) [Melzer, 1997]. The Lajas valley is between our sites at GEOL and PARQ, whose velocities agree at 1σ arguing against significant deformation across the structure. The island of Puerto Rico also is traversed by two major northwest-
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 (GSPRZFZ) and (2) the great southern Puerto Rico fault zone (GSPRZFZ). We note that the baselines between the two continuous lines (Figure 8) crosses the GSPRZFZ. Elastic strain effects from GSPRZFZ on GUEF and PURF zone series are unlikely. Simple two-dimensional elastic strain models using distances from GSPRZFZ of 5 to 25 km for GUEF and PURF, respectively, a baseline length usage between GUEF and PURF of 0.5±0.3 mm/yr, and assumed vertical fast orientation with locking depths of 10–20 km suggest the permissible upper bound on GSPRZFZ motion in 1.5±2.0 mm/yr. Yield evidence for post-Oligocene motion along either the GSPRZFZ or GSPRZFZ 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 southeastem Puerto Rico predicts large lateral linear velocity gradients across the island, extension across the western Puerto Rico trench, and shortening across the Mueertos 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 Mueertos trough south of SW Puerto Rico. On the basis of both observations we argue against significant ongoing rotation about a preaxial axis and favor instead northeastward translation of PRVI relative to North America. The genetic results are supported by focal mechanisms from historic earthquakes, which also yield convergence across the Puerto Rico trench offshore northwestern Puerto Rico [McCann and Perhamnson, 1999; Deng and Sykes, 1995; Dison 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 [Redd et al., 1991].

7.3 Tectonic Escape of PRVI

Jay et al. [1987] and Maughfet and Jumy [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 analogs to the eastward movement 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., 1987; Dison and Man, 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 slope) along a path from the interior of one boundary plate (e.g., North America) across the PRVI block into the interior of the other boundary plate (e.g., Caribbean). 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 total 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 in common with 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 Mueertos 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 579°W, 26° (10) 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 Mueertos trough has a significant left-lateral strike-slip component. Within error, the amount of convergence permissible across the Mueertos 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 Mueertos trough [Ladd and Ruskus, 1978] and seismicity at depths 100 km [Rhines et al., 1983] favors convergence in this region. Two moderate earthquakes (M = 4.7 and 5.0) occurred in August 1993 near the eastern terminus of the Mueertos trough at 65° W where the accretory prism disappears [Jumy et al., 1987; Masson and Scandone, 1991]. Focal mechanisms generated by the Puerto Rico Seismic Network are consistent with left-lateral strike-slip motion along an E-W striking fault [Jumy et al., 1995]. 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 [Helzare, 1997]. Shortening along the Mueertos trough is greatest offshore southwest Puerto Rico and dies out to the east toward the Anegada passage [Masson and Scandone, 1991].

Assuming that motion along the Mueertos 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 bays, and/or other structures offshore southeastern Puerto Rico is minor transension 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 (7.8 < M < 7.5) tsunamigenic earthquake along the north wall of the Virgin Islands basin that caused extensive damage in St. Croix and St. Thomas [Reed and Tubey, 1920].

The kinematics of the eastern Anegada passage can be exam-
in by comparing the velocity of St. Croix (CRO1) with that of
Virgin Gorda (GORD). Results from GORD must be con-
sidered 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 displace-
ment 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-
\( \text{stitial} \) strike slip if the existence of strike-slip motion is
\( \text{summed} \). Jamy et al. [1987] argue that dextral motion along the
Anegada passage began in the Pliocene and is limited to 6-15
\( \text{implying a displacement rate of 1.5-3.7 mm/yr, which may not be}
\( \text{resolvable with GPS geodetic data for several more}
\( \text{years. The lack of earthquakes observed along the Anegada}
\( \text{passage during deployment of a seismic network in the north-
ern Virgin Islands in the 1970s [Frankel et al., 1980] sup-
pports other long recurrence intervals with intervening peri-
ods of seismic quiescence or little motion between GORD and
CRO1. The possibility does exist that CRO1 and GORD ve-
locities are affected by strain accumulation along a faulted, fast
slipping, eastern Anegada Passage fault. We believe this is}
\( \text{ unlikely, however, because of the similarity of CRO1's veloc-
it with the other rigid Caribbean tectons [AVES, SANA, and
AHOI]. The westward motion of Puerto Rico relative to
GORD in the Caribbean reference frame requires E-W exten-
sion between eastern Puerto Rico and the eastern Virgin Is-
\( \text{lands} \) of a few millimeters per year. The location of structures
\( \text{along which extension north of the Anegada passage may be}
\( \text{accommodated} \) 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 res-
pect to western PRVI. The opening rate for the Mona rift can be estimated from comparison of the average GPS-derived ve-
locity for Puerto Rico with those of the northern Dominican Republic. The calculated velocity depends on the amount of
elastic strain accumulation on active faults in the Dominican Republic and the errors associated with the GPS-derived ve-
locities.

The two major E-W to WNW trending fault zones travers-
ing 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 [Prevot et al., 1993; Mamo et al., 1998]. Some deformation also likely oc-
curs 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 earth-
quakes in 1946 and 1948 [Rasso and Villaseñor, 1995; Doo-
lan 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 7.2
mm/yr and 8.7 mm/yr, respectively [Jackson et al., 1989]. Geologically derived Holocene rates yield maximum slip esti-
mates along different segments of the Septentrional fault of
13±4 mm/yr and 21±6 mm/yr [Mambo et al., 1998].

Although the GPS velocities are preliminary because the
godetic data set is spatially limited, they do provide some
constraints on the kinematics of the Mona rift. The west-
ward projections of both the north Hispaniola deformed belt and
the Septentrional fault lie offshore northern Puerto Rico. If we
\( \text{sume that the displacement along the north Hispaniola de-
formed belt and the Septentrional fault is representative of slip}
\( \text{offshore northern Puerto Rico, the GPS-derived velocity for}
\( \text{Puerto Rico with respect to North America should reflect the}
\( \text{integrated slip along offshore structures and the displacement}
\( \text{associated with the Mona rift. The GPS-derived average ve-
locity for Puerto Rico with respect to North America is}
16±4±1 mm/yr toward N80°E at 10° (10). The integrated slip}
\( \text{along the north Hispaniola deformed belt and the Septen-
trional fault estimated from 2-D elastic modeling of strain ac-
cumulation is 21±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 southwestern Puerto Rico, re-
quiring 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
bending faults of the Mona rift.)

The total extension across the Mona rift constrained by
seismic profiles is −6 km [van Gisell et al., 1998]. Using an
opening rate of 3 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 [Reed 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
bending structures of the PRVI block. We argue that at least
one, and possibly two, extensional belts occur between His-
paniola 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 exten-
sion 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 differen-
tial motion between eastern Puerto Rico (ZSU) and Virgin

Gord (GORD) does the remains unmelted within current uncertainties.
PRV) behaves rigidly between these two extensional
zones. The N-S trending Mona rift accommodates ~5
mmyr of sagging opening, which results in a reduction of slip along the
southern plate boundary zone from ~8 mmyr along the
Et-
riggio fault, estimated from 2-D modeling of GPS data ac-
adquired between 1986 and 1995 in Hispaniola [Dixon et al.,
1998], to ~3 mmyr along the Muertes trough. East of Puerto
Rico an additional ~2 mmyr must transfer from the western
Amadea caribbean-northwestern part of the eastern Puerto
Rico trench to allow for little or no motion between GORD and CRIO.
The increased seismicity and focal mechanisms north of
the northeastern Virgin Islands are consistent with this inter-
pretation (Figure 2).

8. Conclusions
We document the existence of a distinct PRVI block within
the diffuse boundary zone between the northern 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 equiva-

cent 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 lim-
ited to the block-boundary structures. The velocity of the
eastern British Virgin Islands (GORD) closely approximates
that of St. Croix (CROI) 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 be-
tween the rigid Caribbean and North American plates, pre-
cluding eastward tec tonic escape of PRVI within the plate
boundary zone.
GPS velocities predict left-lateral transpression across the
Puerto Rico trench and the Muertes trough south of Puerto
Rico, left-lateral transpression across the western Anegada pas-
sage, and opening. The deformation
11

pattern is not compatible with rotation of a rigid PRVI plate, a
conclusion consistent with the location of the southeastern
part of the island of Puerto Rico but is consistent with northward traction of PRVI relative to North America and eastern Hispaniola.

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