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Present motion and deformation of the Caribbean plate: Constraints from new GPS geodetic measurements from Honduras and Nicaragua

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ABSTRACT

Velocities from six continuous and 14 campaign sites within the boundaries of the Caribbean plate, including eight new sites from previously unsampled areas of Honduras and Nicaragua at the western edge of the Caribbean plate, are described and tested for their consistency with Caribbean–North America plate motion and a rigid Caribbean plate model. Sites in central Honduras and Guatemala move 3–8 mm yr^{-1} westward with respect to the Caribbean plate interior, consistent with distributed east-to-west extension in Guatemala and the western two-thirds of Honduras. A site in southern Jamaica moves 8 ± 1 mm yr^{-1} westward relative to the Caribbean plate interior, indicating that most or all of Jamaica is unsuitable for estimating Caribbean plate motion. Two sites in southern Hispaniola also exhibit anomalous motions relative to the plate interior, consistent with a tectonic bias at those sites. An inversion of the velocities for 15 sites nominally located in the plate interior yields a well-constrained Caribbean plate angular velocity vector that predicts motion similar to previously published models. Data bootstrapping indicates that the solution is robust to better than 1 mm yr^{-1} with respect to both the site velocities that are used

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to estimate the plate angular velocity and the site velocity uncertainties. That velocities at seven of eight GPS sites in eastern Honduras and Nicaragua are consistent with the motions of sites elsewhere in the plate interior indicates that much or all of eastern Honduras and Nicaragua move with the plate interior within the 1–2 mm yr^{-1} resolution of our data. It further suggests that the morphologically prominent, but aseismic Guayupe fault of eastern Honduras is inactive. Tests for possible east-to-west deformation across the Beata Ridge and Lower Nicaraguan Rise in the plate interior establish a 95% upper bound of ~2 mm yr^{-1} for any deformation across the two features, significantly slower than a published estimate of 9.0 ± 1.5 mm yr^{-1} during the past 23 Ma for deformation across the Beata Ridge.

Keywords: Caribbean plate, Central America, tectonics, plate motion.

1. INTRODUCTION

Over the past two decades, a fundamental objective of neotectonic research in the Caribbean region has been to determine the present motion of the Caribbean plate using Global Positioning System (GPS) technology (Dixon et al., 1991). Prior to the use of GPS for measuring present plate motions, Caribbean–North America plate velocities were estimated from conventional marine geophysical and seismologic observations. The predictions of the latter estimates varied widely, ranging from 11 ± 6 mm yr^{-1} of sinistral strike-slip motion (Jordan, 1975; Stein et al., 1988; DeMets et al., 1990, 1994) to 37 ± 10 mm yr^{-1} (95% uncertainty) of oblique convergence (Sykes et al., 1982) along much of the Caribbean–North America plate boundary. The wide range of predicted motions resulted from disagreements about which, if any, data constituted reliable measures of Caribbean plate motion, including whether earthquake slip vectors from the Middle America and Lesser Antilles trenches are systematically biased by strain partitioning (Sykes et al., 1982; Stein et al., 1988; DeMets, 1993, 2001; Deng and Sykes, 1995) and whether magnetic anomalies from the Cayman spreading center record the full Caribbean–North America rate (Sykes et al., 1982; Rosencrantz and Mann, 1991).

The first unambiguous geodetic determination of present-day Caribbean plate motion was reported by Dixon et al. (1998) from GPS measurements made at three sites during the early to mid-1990s (CRO1, ROJO, and SANA in Fig. 1). Relative to sites on the North America plate, all three stations moved 18–20 mm yr^{-1}, ~80% faster than predicted by the widely used NUVEL-1A model (DeMets et al., 1994). Subsequent geodetic measurements at additional sites in the eastern Caribbean confirmed this result (MacMillan and Ma, 1999; DeMets et al., 2000; DeMets, 2001; Sella et al., 2002) and further demonstrated that Caribbean–South America plate motion significantly exceeds that predicted by NUVEL-1A (Weber et al., 2001; Sella et al., 2002). It is thus now well established that the Caribbean plate moves significantly faster than predicted by NUVEL-1A.

All previous geodetic models of Caribbean plate motion have two significant, though unavoidable, drawbacks related to their underlying geodetic data. The first is that only one site velocity from the western half of the Caribbean plate was used by previous authors to constrain their estimates of Caribbean plate motion; namely, the velocity of campaign site SANA on San Andres Island, several hundred kilometers east of the Nicaraguan coast (Fig. 1). The lack of independent geodetic observations from the western Caribbean precludes any assessment of the accuracy and precision of published estimates of Caribbean plate motion in this region. Similarly, in the eastern Caribbean, three of the four GPS velocities that anchor all previously published estimates of Caribbean plate motion (sites BARB, CRO1, and ROJO in Fig. 1) are for sites that are close enough to seismically active plate boundary faults to raise concerns that their velocities might be biased by steady interseismic or long-term transient postseismic strain related to the earthquake cycle on those faults (e.g., Pollitz and Dixon, 1998). The sparse data from all areas of the Caribbean plate preclude the usual tests for velocity outliers due to factors such as GPS monument instability or localized tectonic effects.

The scientific motivations for the present analysis are twofold. First, field-based studies of the Caribbean plate boundaries require at minimum an accurately defined estimate of the motion of the plate interior in order to characterize complex deformation in those field areas. These include geodetic studies initiated by several groups in the late 1990s in large areas of Central America and ongoing GPS projects in Hispaniola (Calais et al., 2002), the Lesser Antilles (Jansma and Mattioli, 2005), Jamaica (DeMets and Wiggins-Grandison, 2007), and Venezuela (Weber et al., 2001).

The second motivation for this work is to determine whether the Caribbean plate undergoes significant internal deformation. A variety of geologic and seismic observations have been cited as evidence for such deformation, possibly driven by slow convergence of the South and North America plates across the Caribbean region (Dixon and Mao, 1997; Müller et al., 1999). Holcombe et al. (1990) describe evidence for young faulting and volcanism within seismically active rifts imaged by marine seismic reflection profiles from the Lower Nicaraguan Rise and propose that diffuse east-to-west rifting of the rise occurs in response to sinistral shear along its bounding escarpments. Heubeck and Mann (1991) suggest that the Caribbean plate consists of rigid subplates east and west of the Beata Ridge (BR in Fig. 1) coinciding with the Venezuelan and Colombian basins, and a subplate in western Central

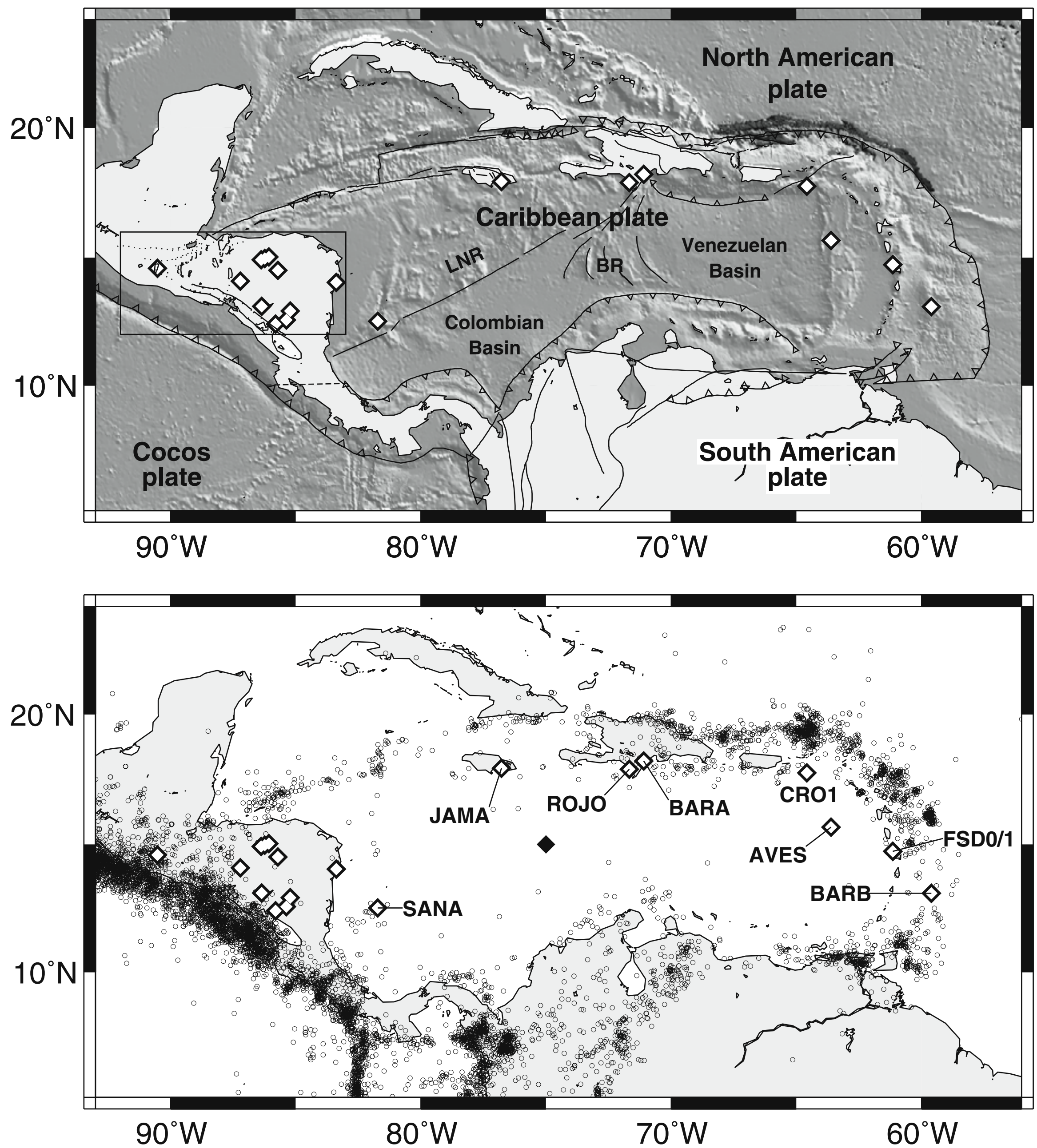

Figure 1. Seismotectonic setting of the Caribbean plate. BR in upper diagram is the Beata Ridge. Line LNR shows the general location and trend of the Lower Nicaraguan Rise, which extends ~1000 km northeastward from the Caribbean coast of Nicaragua toward southern Hispaniola. Open diamonds show locations of GPS sites whose velocities are employed in this study. Filled diamond shows 15°N, 75°W fiducial location employed for the analysis. Area enclosed in rectangle is displayed in Figure 6. All earthquakes above depths of 60 km and with surface- or body-wave magnitudes >3.5 for the period 1963 through 2004 are shown in the lower diagram. AVES, BARA, BARB, CRO1, FSD0/1, JAMA, ROJO, and SANA are site names discussed in text.

American west of the Honduras Depression. Consistent with this interpretation, Leroy and Mauffret (1996) interpret apparently reactivated reverse faults imaged in marine seismic profiles that cross the eastern flank of the Beata Ridge as evidence for contraction across the Beata Ridge and hence deformation within the Caribbean plate. Mauffret and Leroy (1999) further interpret compressional features along the Beata Ridge as evidence for NE-SW shortening between independently moving microplates flanking the Beata Ridge and estimate that the convergence rate across the Beata Ridge has averaged 9 ± 1.5 mm yr^{-1} for the past 23 Ma.

Here, we describe new GPS velocities for 12 sites from the western half of the Caribbean plate (Fig. 1) and use these in combination with the motions of eight additional sites from the central and eastern Caribbean plate to achieve the objectives described above. We first specify and interpret the velocities of all 20 Caribbean plate GPS sites relative to the North America plate in order to identify and exclude velocities that do not record motion of the plate interior. We then invert the velocities of 15 sites whose motions are mutually consistent to determine a best-fitting Caribbean plate angular velocity vector. We describe and interpret residual site velocities with respect to the predictions of the best-fitting angular velocity vector and employ formal data importances to determine the amount of information that the individual site velocities contribute to our best-fitting model. In light of evidence that a single station velocity (CRO1) supplies 40% of the model information, we employ data bootstrapping to determine how robust our estimate of Caribbean plate motion is with respect to the 15 site velocities and their estimated uncertainties. We then construct an alternative best estimate of Caribbean plate motion that more evenly distributes the information contributed by the site velocities and excludes two sites in the eastern Caribbean that exhibit evidence for small tectonic biases. We conclude by estimating for the first time a rigorous upper bound on possible east to west internal deformation of the Caribbean plate.

2. GPS DATA AND ANALYSIS

Table 1 summarizes information about the 20 campaign and continuous GPS measurements used in the analysis (Fig. 1). From Central America, we employ new data from 11 stations, eight of which are campaign sites that we installed and first occupied in 2000–2001 in aseismic, interior areas of Nicaragua and Honduras. Observations at these sites span intervals of 2.1 yr (PUEC) to 5.2 yr (CMP1). The other three Central American sites are the continuous stations ESTI, GUAT, and TEGU/TEG1, which were installed in 2000 and are operated by the U.S. National Oceanic and Atmospheric Administration (NOAA). We also update the velocity for site SANA, located on San Andres Island east of Nicaragua, using new data collected in 2003. From the central and eastern areas of the Caribbean plate, we use continuous data from sites in Jamaica (JAMA), southern Hispaniola (BARA), the Virgin Islands (CRO1), and Barbados (BARB), complemented by campaign data from sites AVES, ROJO, FSD0, and FSD1.

We exclude all sites on the Puerto Rico–Virgin Islands block, which moves westward at a rate of 2.6 ± 1.0 mm yr^{-1} relative to the Caribbean plate interior (Jansma and Mattioli, 2005), and also exclude all sites in Hispaniola that are located north of the Enriquillo fault, which accommodates significant long-term

TABLE 1. GPS SITE INFORMATION AND OCCUPATION HISTORY

Site name (country)	Lat (°N)	Long (°W)	Station days occupied per calendar year						Site velocity mm yr^{-1}	
			2000	2001	2002	2003	2004	2005	North	East
CMP1 (Honduras)	14.5092	85.7146	3					2	5.3 ± 2.0	10.6 ± 3.0
GLCO (Honduras)	15.0298	86.0699	2				3	2	4.7 ± 2.2	8.6 ± 3.3
MNTO (Honduras)	14.9168	86.3805	3				3		6.1 ± 2.1	11.1 ± 3.2
SFDP (Honduras)	14.9659	86.2449	3				3		5.4 ± 2.1	9.7 ± 3.5
PORT (Nicaragua)	12.5731	85.3671	3		4	4			3.4 ± 1.6	10.8 ± 6.2
PUEC (Nicaragua)	14.0421	83.3820		4		4			2.8 ± 4.4	6.4 ± 5.9
RIOB (Nicaragua)	12.9209	85.2206	4		4	4			5.6 ± 1.8	9.6 ± 7.8
TEUS (Nicaragua)	12.4098	85.8136	5		5	5			4.7 ± 2.4	10.0 ± 2.0
TEGU (Honduras)	14.0905	87.2056	245	282	333	236	366	64	3.7 ± 0.7	7.4 ± 0.8
GUAT (Guatemala)	14.5904	90.5202	156	333	342	314	326	261	2.1 ± 0.6	2.1 ± 0.8
ESTI (Nicaragua)	13.0996	86.3621	203	325	332	56			12.8 ± 1.1	10.9 ± 1.6
SANA (Colombia)	12.5238	81.7294	Occupied 1994 (5), 1996 (3), 1998 (6), 2000 (6), and 2003 (5)						6.9 ± 0.4	13.8 ± 1.2
JAMA* (Jamaica)	17.9390	76.7810	258	356	325	138			10.1 ± 0.7	1.6 ± 0.9
BARB (Barbados)	13.0879	59.6091	Semi-continuous from 1997–2001 (580 station days)						15.2 ± 1.0	10.8 ± 1.8
CRO1 (Virgin Isl.)	17.7569	64.5843	Continuous from Oct. 1995-present						12.5 ± 0.4	9.9 ± 0.6
BARA (Dom. Rep.)	18.2087	71.0982				322	325	245	7.6 ± 0.9	8.0 ± 0.9
ROJO (Dom. Rep.)	17.9040	71.6745	Occupied 1994 (9), 1995 (2), 1998 (3), and 2001 (2)						7.8 ± 1.5	11.1 ± 2.4
AVES (Venezuela)	15.6670	63.6183	Occupied 1994 (18) and 1998 (10)						13.3 ± 2.0	11.7 ± 2.9
FSD0 (Martinique)	14.7348	61.1467	Occupied 1994 (4), 1998 (5), and 1999 (4)						15.0 ± 2.0	12.4 ± 3.0
FSD1 (Martinique)	14.7349	61.1465	Occupied 1994 (5), 1998 (11), and 1999 (3)						14.9 ± 1.8	14.2 ± 2.7

Note: Site velocities are relative to ITRF2000. Uncertainties are standard errors.
*Site JAMA also has 88 days of data from 1999.

slip relative to the plate interior (Mann et al., 1995, 2002; Calais et al., 2002).

All GPS code-phase measurements employed for this analysis, including observations from 151 continuous stations that anchor our North America plate reference frame, were analyzed using GIPSY software from the Jet Propulsion Laboratory (JPL). We employed a standard point-positioning analysis strategy (Zumberge et al., 1997) combined with resolution of integer phase ambiguities. Daily GPS station coordinates were first estimated in a nonfiducial reference frame (Heflin et al., 1992) employing precise fiducial-free satellite orbits and clocks from JPL. The loosely constrained station coordinates were then transformed to ITRF2000 (Altamimi et al., 2002) using daily seven-parameter Helmert transformations supplied by JPL. We also estimated and removed daily and longer-period regionally correlated noise between sites using a technique described by Marquez-Azua and DeMets (2003). Daily repeatabilities in the north, east, and down components of the GPS site coordinates are 2–4 mm, 3–5 mm, and 8–10 mm, respectively. Uncertainties in the GPS site velocities are estimated using procedures described by Mao et al. (1999), with white and flicker noise estimated from individual GPS time series and a further assumed contribution of 1 mm per √yr from random monument walk.

3. RESULTS

3.1. Plate-Wide Velocity Field Relative to the North America Plate

We begin by examining the velocities of all 20 GPS sites relative to the North America plate interior, which constitutes a natural geological reference frame for sites located along the Lesser Antilles trench and northern boundary of the Caribbean plate. The angular velocity vector that specifies motion of the North America plate relative to ITRF2000 is determined from an inversion of the velocities of 151 sites from the plate interior, based on our own analysis of continuous data from these stations (Table 2). We omitted the velocities of all sites within 2000 km of Hudson Bay, where glacial isostatic rebound measurably affects site motions (Park et al., 2002; Mazzotti et al., 2005; Calais et al., 2006). We also excluded sites west of the Rio Grande Rift to avoid biases from any slow deformation west of the rift. The weighted root-mean-square residual motions of the 151 North America plate sites relative to the best-fit model predictions average 0.8 mm yr^{-1} in both the north and east velocity components. Uncertainties in the velocities predicted by the well-constrained North America plate angular velocity vector are smaller than ± 0.1 mm yr^{-1} and ± 0.8° at locations in the Caribbean and are thus not a limiting factor in the analysis described below.

Figure 2 shows the 20 Caribbean GPS velocities after their transformation into the North America plate reference frame. Velocities range from 11 to 23 mm yr^{-1} and generally point toward N75°E ± 5° (Figs. 2 and 3). More than half of the velocities agree within their errors with the predictions of previous GPS-based models for Caribbean–North America plate motion (Dixon et al., 1998; DeMets, 2001; Sella et al., 2002). In particular, the four new campaign sites in eastern and central Honduras (CMP1, GLCO, MNTO, and SFDP) have an average weighted velocity of 19.3 ± 1.7 mm yr^{-1} toward N73.7°E ± 3° (see vector labeled "HND" in Fig. 2), and four of the five Nicaraguan sites (PORT, PUEC, RIOB, and TEUS) have an average weighted velocity of 17.8 ± 1.7 mm yr^{-1} toward N76.7°E ± 4° (see "NIC" in Fig. 2). Both averages are consistent within errors with the motion expected for sites that lie on the Caribbean plate interior (Fig. 3).

The motions of five sites depart significantly from their expected motions. Site ESTI in Nicaragua moves ~4 mm yr^{-1} faster than and 20° counterclockwise from the other Nicaraguan sites (Fig. 2). For security and logistical reasons, the GPS antenna at ESTI is mounted on a steel tower >7 m high (M. Chin, 2005, personal commun.). We thus suspect that monument instability may be the cause of the anomalous motion at ESTI and exclude this velocity from further analysis. Sites TEGU and GUAT, which are located ~150 km and ~500 km west of the cluster of four GPS sites in central eastern Honduras, move in the same direction as other nearby Central American sites (Figs. 2 and 3), but at rates that are 3 ± 1 mm yr^{-1} and 8 ± 1 mm yr^{-1} slower than predicted for sites on rigid Caribbean lithosphere. That the motions of TEGU and GUAT become progressively faster to the west is consistent with geologic (Manton, 1987) and seismic (Guzman-Speziale, 2001) evidence for significant extension across much of Honduras and Guatemala. The pattern of site velocities defined by the four campaign sites in eastern and central Honduras and continuous sites TEGU and GUAT strongly suggests that the western limit of stable areas of the Caribbean plate interior lies between TEGU and the four GPS sites in eastern-central Honduras.

TABLE 2. BEST-FITTING CARIBBEAN PLATE ANGULAR VELOCITY VECTOR INFORMATION

Plate pair	No. of sites	Angular velocity vector			Angular velocity vector covariances					
		λ (°N)	φ (°E)	ω (degrees/m.y.)	α_{xx}	α_{yy}	α_{zz}	α_{xy}	α_{xz}	α_{yz}
CA-ITRF2000	15	36.3	–98.5	0.255	0.350	3.017	0.520	–0.864	0.263	–0.859
NA-ITRF2000	151	–7.64	–86.21	0.196	0.011	0.182	0.107	0.015	–0.011	–0.125
CA-NA (15)	166	75.9	191.5	0.182	0.361	3.199	0.627	–0.849	0.252	–0.984
CA-ITRF2000	13	34.3	–96.8	0.270	0.132	0.831	0.175	–0.262	0.000	–0.184
CA-NA (13)	164	75.0	215.3	0.185	0.143	1.013	0.282	–0.247	–0.011	–0.309

Note: CA—Caribbean plate; NA—North America plate. First plate rotates counterclockwise around the pole relative to the second. Latitude, longitude, and angular rotation rate are specified by λ, φ, and ω, respectively. Elements of the symmetric 3 × 3 variance-covariance matrix are given in units of 10^{-8} radians^2 per m.y.^{2}. Variance-covariance matrix for the 13-site CA-ITRF2000 angular velocity vector is derived from bootstrapped solutions (see text).

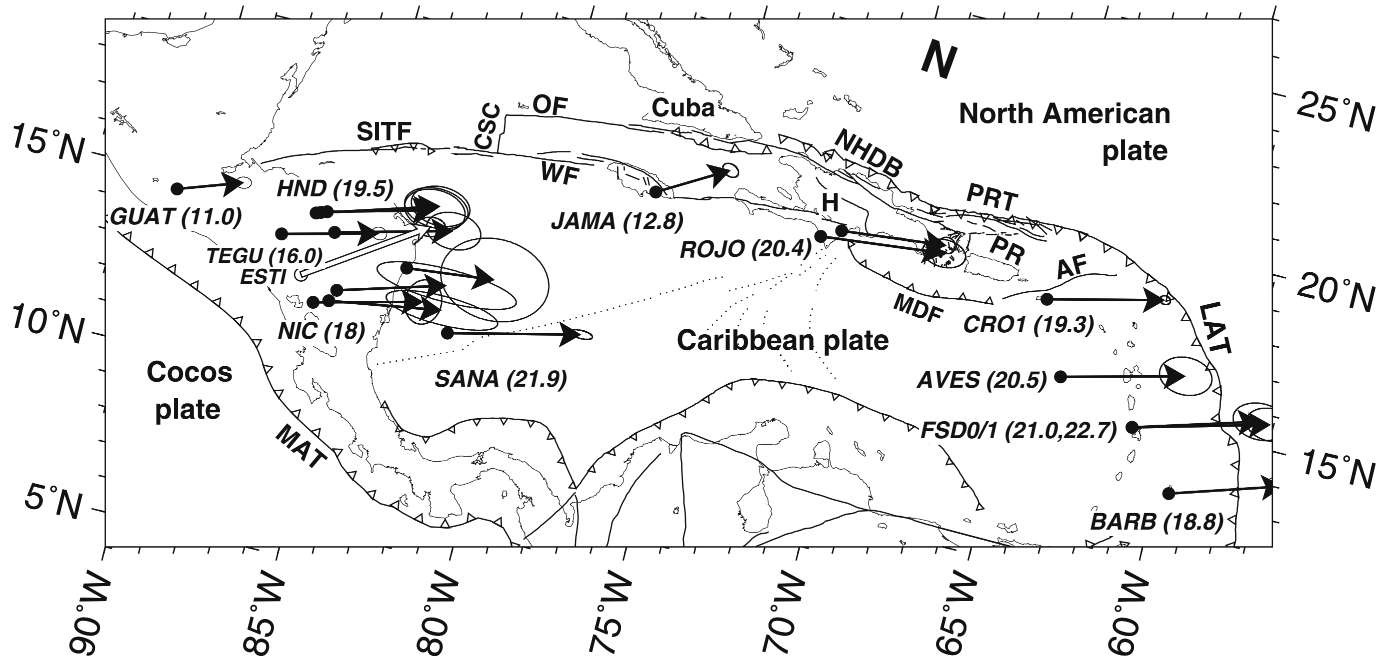

Figure 2. GPS site velocities relative to the North America plate on an oblique Mercator map projected about the best-fitting Caribbean–North America pole of rotation. Numerals by site names give the site rates in millimeters per year. Open arrow indicates motion of site ESTI, where the antenna is mounted on a tall steel tower of questionable stability. The location of GPS site BARA discussed in the text is shown in Figure 1. AF—Anegada fault; CSC—Cayman spreading center; H—Hispaniola; HND—; LAT—Lesser Antilles trench; MAT—Middle America trench; MDF—Muertos deformed belt; NHDB—Northern Hispaniola deformed belt; NIC—Nicaragua; OF—Oriente fault; PR—Puerto Rico; PRT—Puerto Rico trench; SITF—Swan Islands transform fault; WF—Walton fault. AVES, BARB, CRO1, GUAT, ESTI, FSD0/1, JAMA, ROJO, SANA, and TEGU are site names discussed in the text.

Along the northern boundary of the Caribbean plate, the motion of site JAMA in southern Jamaica is 7 ± 1 mm yr^{-1} slower than and 17° counterclockwise from the velocity predicted for a Caribbean plate interior site (Figs. 2 and 3). Nineteen other GPS sites in Jamaica exhibit similar velocity deficits (DeMets and Wiggins-Grandison, 2007), indicating that most or all Jamaican GPS sites are unsuitable for estimating Caribbean plate motion.

In Hispaniola, site BARA also moves significantly slower (by 2 ± 1 mm yr^{-1}) than predicted for a plate interior site (Fig. 3). Its slip deficit with respect to the full Caribbean–North America rate is consistent with a GPS velocity gradient in Hispaniola that is interpreted by Dixon et al. (1998), Calais et al. (2002), and Mann et al. (2002) as evidence for elastic strain accumulation from locked plate boundary faults within and north of Hispaniola. Site BARA is thus located within the zone of interseismic elastic deformation associated with plate boundary faults in Hispaniola, making its velocity unsuitable for estimating the motion of the Caribbean plate interior.

We conclude that sites GUAT, TEGU, JAMA, and BARA are located in probable zones of distributed deformation and that monument instability may bias the velocity at site ESTI. Their velocities are thus not used below to constrain Caribbean plate motion.

3.2. Best-Fitting 15-Station Caribbean Plate Model and Residual Velocities

We next invert velocities of the 15 sites (Table 1) that appear to move with the Caribbean plate interior to define a best-fitting angular velocity vector for Caribbean plate motion relative to ITRF2000. The north and east velocity components for each site are weighted in the inversion by the reciprocal of their squared uncertainties (their variances), thereby ensuring that velocities for sites such as CRO1 with long, continuous time series contribute more to the solution than do sites that are infrequently occupied or that have shorter time series. The best-fitting angular velocity vector (Table 2) fits the 15 site velocities well, with respective weighted root-mean-square misfits of 0.8 mm yr^{-1} for the north velocity component and 1.3 mm yr^{-1} for the east velocity component. The misfits are comparable to site velocity misfits reported for other plates (Sella et al., 2002), but are smaller by ~25% than the assigned site velocity uncertainties. We therefore multiplied the angular velocity vector variances and covariances by reduced chi-square for the best-fitting solution (0.54) to ensure that the angular velocity uncertainties accurately reflect the dispersion of the site velocities with respect to the model predictions.

Figure 4 shows the site data importances, which constitute a formal measure of the amount of information that each site

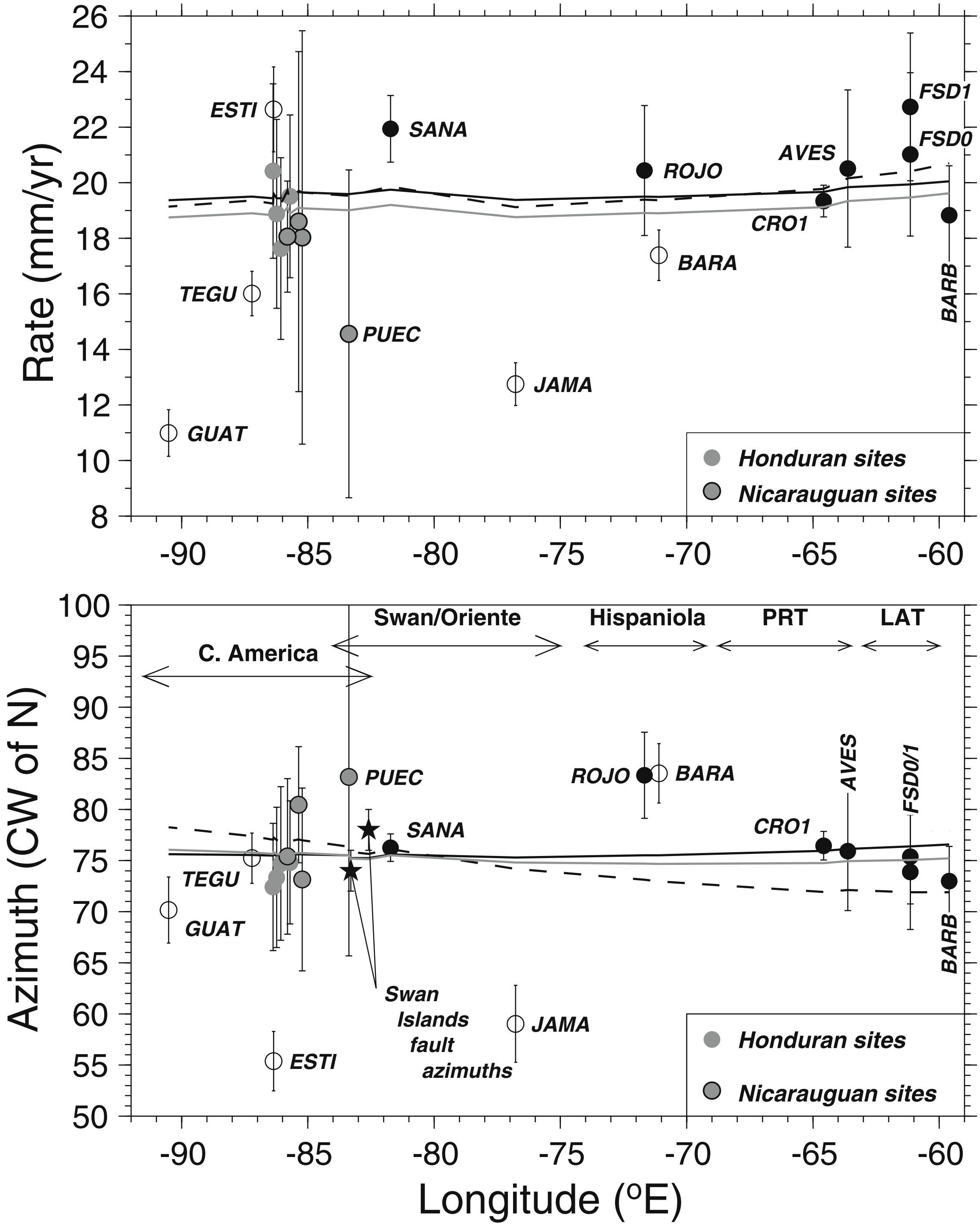

Figure 3. Rates (upper) and directions (lower) of GPS sites relative to North America plate. Solid and shaded circles show GPS velocities that are used to derive the best-fitting Caribbean–North America angular velocity, whose predictions are shown by the solid black line. Dashed and shaded lines show predictions of Caribbean–North America angular velocity vectors from DeMets (2001) and Sella et al. (2002), respectively. Open circles show the motions of sites that are not used to derive the best-fitting model due to obvious tectonic or other biases in their motions. Swan Islands transform fault azimuths in lower panel are from multibeam seafloor mapping (Rosencrantz and Mann, 1991). LAT—Lesser Antilles trench; PRT—Puerto Rico trench. AVES, BARA, BARB, CRO1, GUAT, ESTI, FSD0, FSD1, JAMA, PUEC, ROJO, SANA, TEGU are site names discussed in the text.

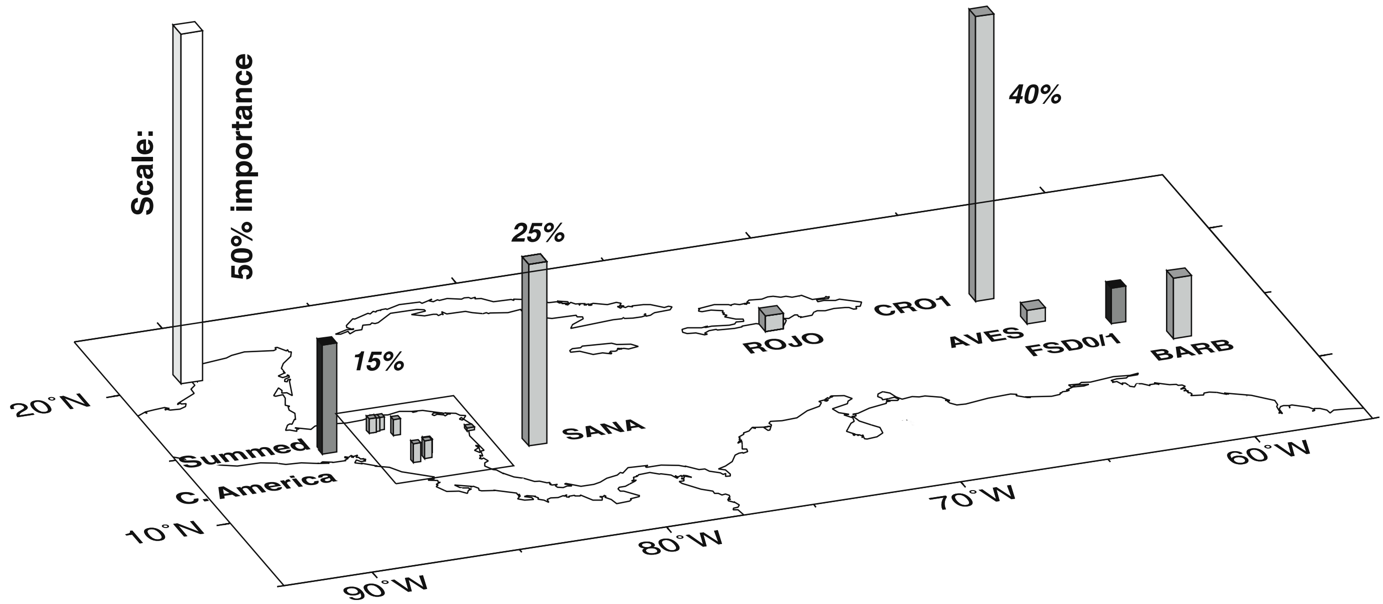

Figure 4. Data importances for velocities of Caribbean and Central American GPS sites that are used to derive the best-fitting, 13-station Caribbean-ITRF2000 angular velocity vector (Table 2). Darker gray-shaded bar shows the summed importances of the eight Central American sites within the boxed region. AVES, BARB, CRO1, FSD0/1, ROJO, and SANA are site names discussed in the text.

velocity contributes to the best-fitting angular velocity vector (Minster et al., 1974). For our application, the data importances are determined from the relative uncertainties of the individual site velocities and their geographic locations with respect to the other sites and the pole of rotation. They are thus a useful guide to the strengths and weaknesses of a data-poor model such as our own and can be used to develop strategies to overcome potential problems.

The best-fitting angular velocity vector derives much (40%) of its information from the velocity for site CRO1 (Fig. 4). This high importance is attributable to the small velocity uncertainty for CRO1, which has a 10-yr-long continuous time series. In contrast to CRO1, the other five sites in the eastern Caribbean have a cumulative importance of only 18%. Our own (and previous) estimates of Caribbean plate motion thus rely heavily on the velocity for CRO1 and, by implication, on the possibly incorrect assumption that site CRO1 accurately records motion of the undeforming Caribbean plate lithosphere. The good fit of the model to the velocity at CRO1 (Fig. 5), better than for any of the other three sites in the eastern part of the plate, results from the site velocity's high importance in the model and by itself cannot be taken as evidence that the site moves with the plate interior.

In the western region of the plate, the eight Honduran and Nicaraguan sites contribute a cumulative 15% of the model information, less than is contributed by site SANA (25%), which has been occupied more frequently and over a significantly longer period than have the eight Central American sites. Relative to previous solutions (e.g., DeMets et al., 2000; Sella et al., 2002), which use only the velocity at SANA to constrain plate motion west of Hispaniola, our model information is distributed more evenly between the western and eastern regions of the Caribbean plate, mainly because motion for the western half of the plate is now estimated from nine GPS velocities instead of just the velocity at site SANA. As a consequence, more meaningful tests of model robustness and plate rigidity are possible (described below).

Figures 5 and 6 show the residual velocities at all the sites with respect to motion predicted by our best-fitting, 15-station Caribbean-ITRF2000 angular velocity vector (Table 2). If the 15 site velocities and their estimated uncertainties accurately describe motion of the plate interior, the pattern of residual site velocities should be random in stable areas of the plate and show some systematic pattern in areas of diffuse or concentrated deformation. We next describe the residual site velocities, with particular attention to any evidence for tectonic or other systematic biases at individual sites.

Eastern and Central Caribbean

The velocities at sites AVES and CRO1 differ insignificantly (0.7 ± 2.8 mm yr^{-1} and 0.4 ± 0.6 mm yr^{-1}, respectively) from the velocities predicted by the best-fitting CA-ITRF2000 angular velocity vector (Fig. 5). The velocity for AVES contributes only 5% of the model information to the best-fitting angular velocity vector (Fig. 4). The small residual velocity at AVES thus constitutes useful evidence that the site is located in a stable area of the plate interior. Similarly, residual velocities at campaign sites FSD0 and FSD1 are both smaller than their estimated rate uncertainties of ± 3.5 mm yr^{-1}, indicating that neither moves relative to the plate interior at a rate that exceeds its estimated uncertainty.

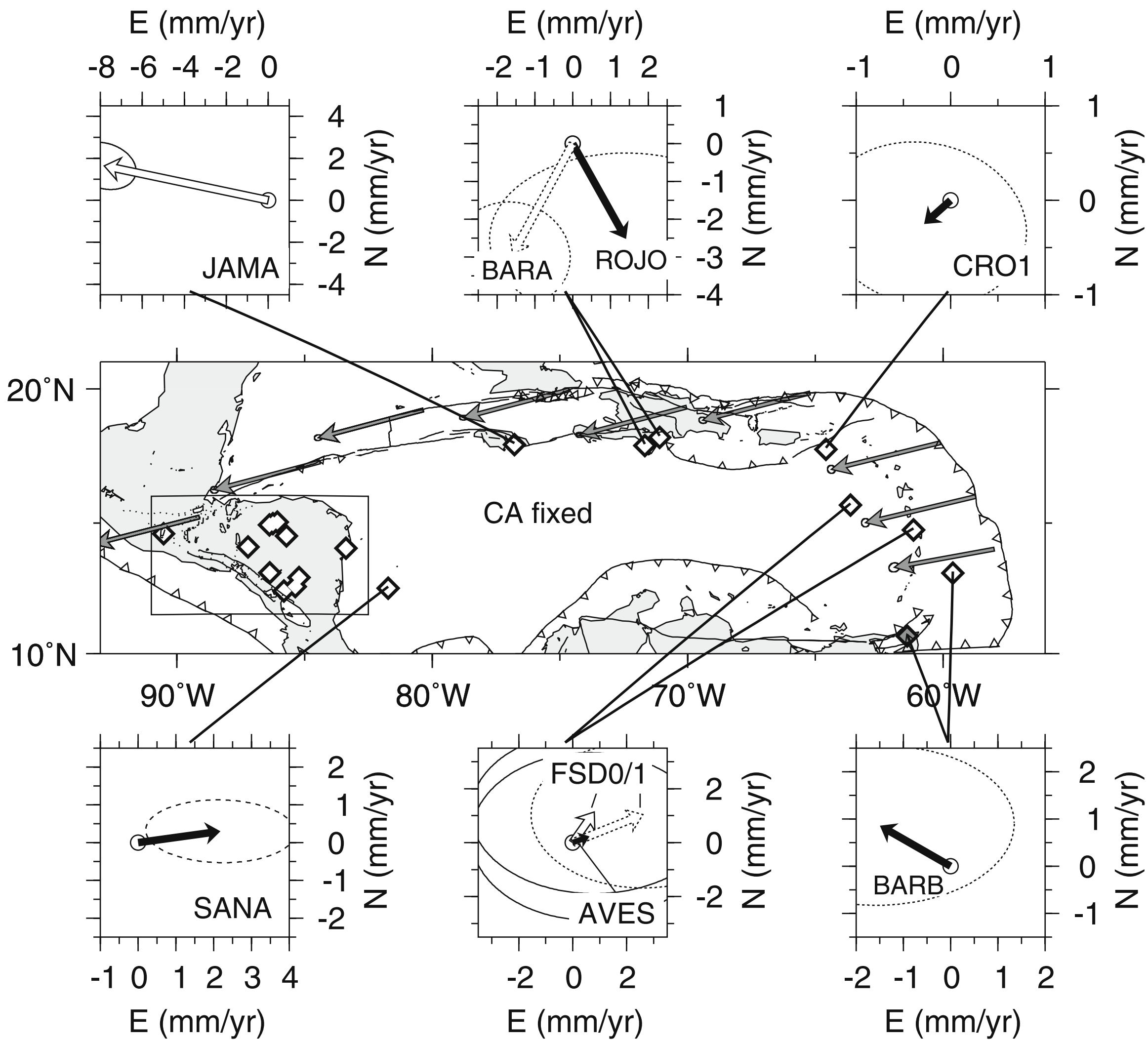

Figure 5. Velocities of circum-Caribbean GPS sites relative to the Caribbean plate (CA) interior after removing motion predicted by the best-fitting Caribbean-ITRF2000 angular velocity vector (Table 2). North America plate movement relative to the Caribbean plate (Table 2) is shown by shaded arrows for points along the plate boundary. Site velocity ellipses are two-dimensional, 1σ. Residual site velocities shown with open arrows were not used to derive the best-fitting CA-ITRF2000 angular velocity vector. Rectangle encloses area shown in Figure 6. AVES, BARA, BARB, CRO1, FSD0/1, JAMA, ROJO, and SANA are site names discussed in the text.

The residual velocity at site BARB points away from the Lesser Antilles trench toward the plate interior (Fig. 5). Although the misfit of 1.7 ± 1.7 mm yr^{-1} is only marginally significant, the geologic setting of this site makes it unlikely that it is part of the plate interior. Geological mapping indicates that Barbados, which is located at the crest of the extensive Lesser Antilles accretionary prism, formed by offscraping, back rotation, and shortening of marine sediments (Speed, 1983). The trench-normal component of the residual motion at BARB is consistent with active shortening of the accretionary wedge, possibly via permanent deformation within the wedge or by elastic strain from frictional locking of the subduction interface downdip from Barbados. Evidence for slow motion (~1 mm yr^{-1}) toward the plate interior at other sites in the Lesser Antilles (G. Mattioli, personal commun., 2006) suggests that the observed residual motion at site BARB is real and that surface deformation along the volcanic arc is probably influenced at a measurable level by elastic strain accumulation driven by frictional coupling across the Lesser Antilles subduction interface. Given the available observations, we exclude the velocity from BARB from the 13-station velocity model described in Section 3.4.

The residual velocities at sites BARA and ROJO in southern Hispaniola both have southward components (Fig. 5), increasing from 2 mm yr^{-1} at ROJO to 3 mm yr^{-1} at BARA. The southward motions of both sites toward the plate interior are consistent with a previously described gradient in the boundary-normal components of motion at other GPS sites from Hispaniola (Calais et al., 2002). Calais et al. interpret this gradient as an elastic response to

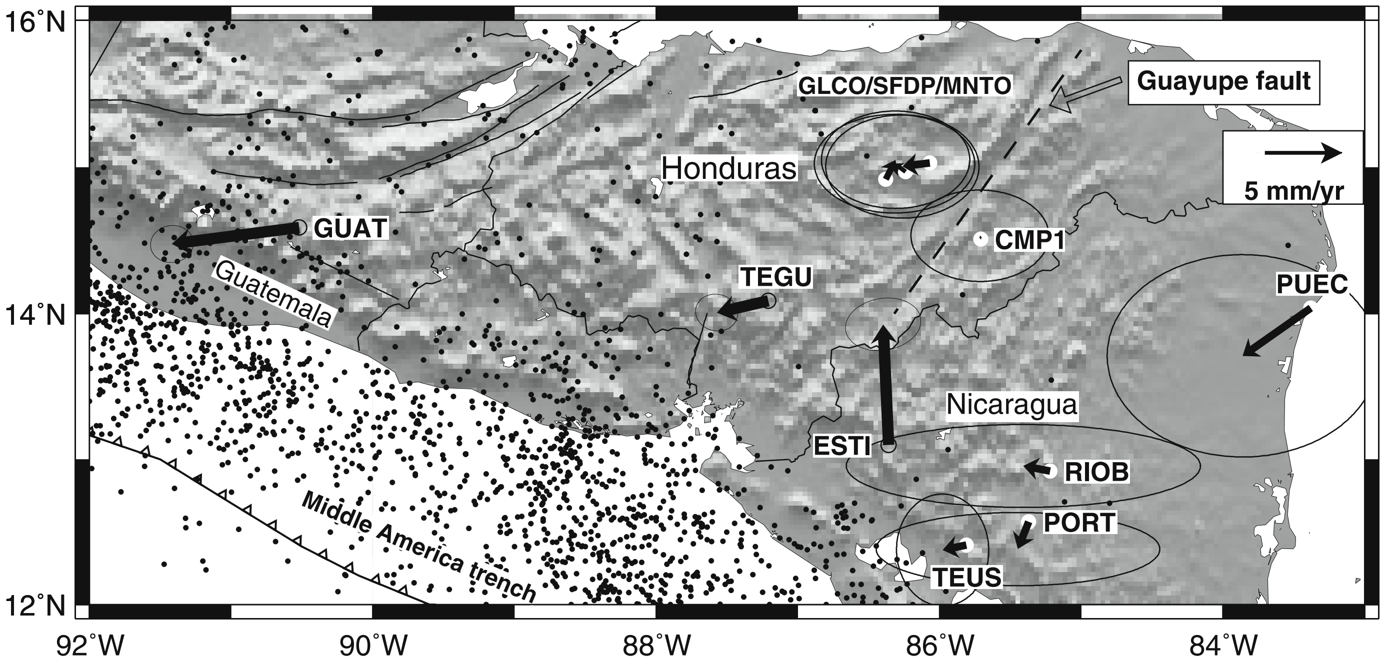

Figure 6. Residual velocities of Central American GPS sites relative to motion predicted by the best-fitting Caribbean-ITRF2000 angular velocity vector (Table 2). Site velocity ellipses are two-dimensional, 1σ. Open circles indicate epicenters of earthquakes located above a depth of 60 km with surface- or body-wave magnitudes greater than 3.5 for the period 1963 through 2004. CMP1, ESTI, GLCO/SFDP/MNTO, GUAT, PUEC, PORT, RIOB, TEGU, and TEUS are site names discussed in the text.

5 ± 2 mm yr^{-1} of dip-slip motion along the northern Hispaniola thrust fault (NHDP in Fig. 1), constituting roughly half of the10 ± 1.5 mm yr^{-1} of boundary-normal convergence that should occur across Hispaniola if oblique convergence is fully partitioned into boundary-parallel and boundary-normal components (DeMets et al., 2000). Given the likelihood that the misfits at BARA and ROJO represent tectonic biases due to their proximity to active faults in Hispaniola, we exclude both site velocities from our 13-station solution that is described in Section 3.4.

Western Caribbean

For the nine sites from the western Caribbean whose velocities are used to estimate the best-fitting CA-ITRF2000 angular velocity vector, only the velocity for site SANA, which has the longest occupation history of any site in the western Caribbean, is significantly misfit (Fig. 5). It seems unlikely that the misfit is attributable to monument instability because the monument is embedded in bedrock. Elastic effects from major plate boundary faults are also an implausible explanation given that SANA is located >200 km from any major plate boundary faults. San Andres Island is, however, located adjacent to the seismically active San Andres Trough (Fig. 1), within a region of postulated distributed deformation in the Lower Nicaraguan Rise (Holcombe et al., 1990).

Residual velocities from the eight sites in Honduras and Nicaragua whose velocities are used to estimate Caribbean plate motion are smaller than their estimated standard errors (Fig. 6), with misfits for seven of the eight sites of only 0.2–1.9 mm yr^{-1}. The largest misfit occurs for site PUEC, which has shortest occupation history (2.1 yr) of the 20 sites we use. PUEC is located on the roof of a single-story concrete building, which may also contribute to the site's residual velocity. That all eight velocities from Honduras and Nicaragua are fit within their uncertainties despite their low data importances demonstrates that they are consistent with the higher importance velocities for sites in the eastern Caribbean (particularly CRO1). The three Honduran sites (GLCO, MNTO, and SFDP) that are clustered northwest of the Guayupe fault (Fig. 6) exhibit no coherent pattern in their small residual velocities and no net motion relative to site CMP1, located immediately southeast of the Guayupe fault. The Honduran velocities thus suggest there is little or no slip along the Guayupe fault.

3.3 Model Sensitivity and Robustness

The 15-station best-fitting solution has several potential weaknesses that could degrade its accuracy. Prominent among these is its over-dependence on the velocity for site CRO1, which makes the solution sensitive to any systematic tectonic or other biases at that site. Of further concern are the possible tectonic biases in the velocities for sites BARB and ROJO. In light of these potential problems, we use two techniques to examine the robustness of our 15-station model predictions. We first examine the effects of the individual site velocities on the predictions of

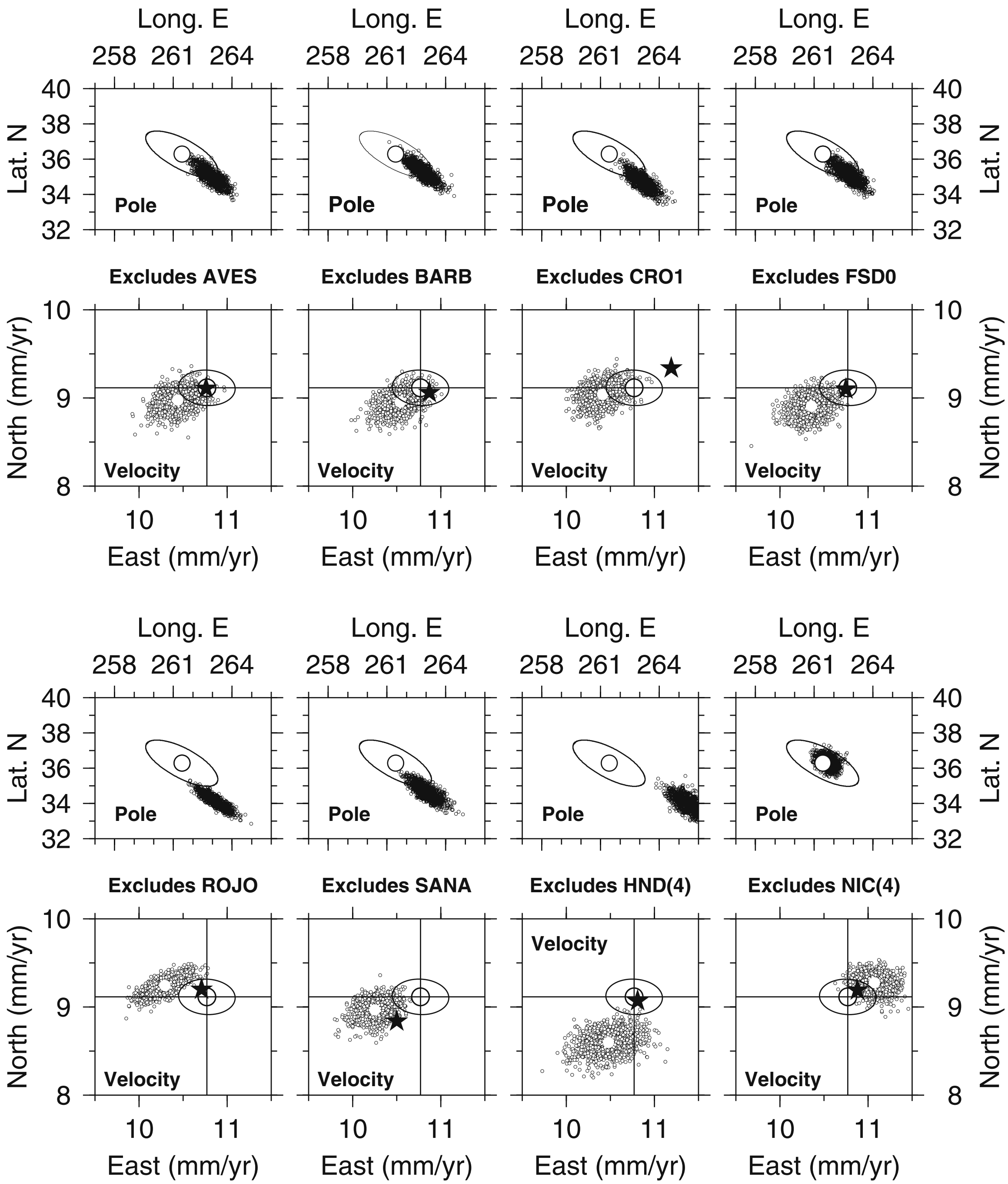

Figure 7. Outcome of data sensitivity and bootstrap analyses for the 15-station best-fitting Caribbean plate solution. Procedures are described in the text. HND and NIC represent the four Honduran site velocities and four Nicaraguan site velocities, respectively. Sub-panels labeled "Pole" show the 15-station, best-fitting pole (open circle), its two-dimensional, 1σ confidence ellipse, and bootstrap pole locations (dots) that are derived from bootstrapping of velocity subsets that exclude the site velocity or velocities that are specified beneath the sub-panel. Sub-panels with velocity estimates show only the velocity vector endpoints and exclude the vector origins (0, 0). Open circles and ellipses that are centered on the crosshairs are the velocities and two-dimensional, 1σ uncertainties at 15°N, 75°W derived from the 15-station, best-fitting angular velocity vector and its covariances. Stars show the velocities at 15°N, 75°W estimated from 14-station models that exclude one station velocity and weight the remaining 14 site velocities by their formal uncertainties from Table 1. The tiny circles in the velocity sub-panels show velocities at 15°N, 75°W predicted by the bootstrap poles. The open circle in the cloud of bootstrapped velocity predictions is the mean bootstrap velocity prediction. AVES, BARB, CRO1, FSD0, ROJO, and SANA are site names discussed in the text.

the best-fitting Caribbean plate angular velocity vector. We then examine whether our estimate of Caribbean plate motion changes significantly if we force a more even distribution of the kinematic information between the site velocities than is the case for the 15-station angular velocity vector that is described at the beginning of Section 3.2.

To examine the effect of the individual site velocities on the best-fitting model estimates, we systematically excluded the velocity of each of the 15 GPS sites, inverted the remaining 14 site velocities and their formal errors, and used the resulting best-fitting angular velocity vector to predict a velocity at 15°N, 75°W, near the center of the Caribbean plate. As is shown in Figure 7, the largest changes in the velocities predicted at this location are 0.4–0.5 mm yr^{-1} and 0.4° in direction and occur if we exclude either of the two highest importance site velocities, those for CRO1 or SANA. In contrast, omitting the velocities for the lower importance sites results in almost no change in the resulting model prediction, primarily because the low importance sites by definition have only a small influence on the best-fitting solution. Consequently, we conclude that the site motions estimated from the best-fitting 15-site angular velocity vector are robust at the level of 0.5 mm yr^{-1} and 0.4° with respect to the site velocities that are used to derive it.

Our assessment of the model robustness implicitly assumes that the formal site velocity uncertainties are approximately correct. If, however, one or more site velocities are affected by any tectonic or other systematic biases, such as monument instability, the formal velocity errors for those sites will underestimate the true errors and hence overweight those velocities in the inversion. Tectonic biases are of potential concern at four of the fifteen stations. Of particular concern is geodetic evidence for 1.9 ± 0.2 mm yr^{-1} of extension between CRO1 and a site in eastern Puerto Rico (Jansma and Mattioli, 2005), which may indicate there are active faults between or close to these two sites. For example, if faults in the Anegada basin (Masson and Scanlon, 1991), located adjacent to site CRO1, are actively accumulating interseismic elastic strain, this strain will bias the motion of site CRO1 relative to its motion with the rigid plate interior. Similarly, the poorly fit velocity at SANA on San Andres Island is also of concern given that the island is located adjacent to the San Andres Trough, where active seismicity, folding of young strata, and young volcanism are consistent with active extension (Holcombe et al., 1990). Finally, tectonic biases ≥1 mm yr^{-1} may exist in the velocities at BARB and ROJO, as described in Section 3.2.

Given the likelihood that one or more of the site velocities employed to derive our 15-station best-fitting angular velocity vector is influenced by nearby deformation, we explored a wider range of possible models for Caribbean plate motion by using data bootstrapping to expand the range of velocity weighting schemes (Efron and Tibshirani, 1986). Bootstrapping employs repeated random sampling of a parent data population to estimate alternative best-fitting models. For our application, we constructed 15 distinct "parent" velocity subsets as a starting point for the bootstrap analysis. Each of the parent velocity subsets excludes the velocity for one of the 15 GPS sites employed for our best-fitting model determination (Section 3.2), and hence establishes a basis for determining the influence of each of the 15 sites on the model.

From each of the 15 parent velocity subsets, we randomly selected 14 site velocities, saved the random data sample, and repeated the process so as to generate 1000 bootstrap data sets per parent velocity population. All of the site velocities in the parent data set are assigned identical uncertainties. As a consequence, the relative weights of the site velocities within any randomized sample are determined by the frequencies with which the velocities are randomly selected for that sample. Our bootstrapping procedure thus samples 1000 alternative data weighting schemes per parent velocity subset and is hence non-prejudicial with respect to the existence of tectonic or systematic biases in an individual site velocity. Our procedure implicitly assigns a weight of zero to the velocity of the site that is excluded from a given parent velocity subset, thereby allowing us to determine the influence of each of the 15 site velocities within the context of the bootstrap analysis.

Each bootstrap sample was inverted to derive its corresponding best-fitting angular velocity vector, giving rise to 15,000 individual bootstrap solutions. Figure 7 illustrates the results for the sites with the highest data importances in the 15-station best-fitting model. The average site velocities that are predicted by the bootstrap models never deviate by more than 0.6 mm yr^{-1} or 1.7° from the linear velocity predicted by our best-fitting 15-station model. The difference at CRO1, the most important site, is only 0.4 mm yr^{-1} and 0.8°. We conclude that the best-fitting 15-station model described in Section 3.2 is robust at a level of ± 0.6 mm yr^{-1}. Surprisingly, all but one of the averaged bootstrap velocities are slower than those predicted by the 15-station best-fitting model, thereby implying that slower plate motion is a robust characteristic of models that more evenly distribute the velocity information between the sites. The effect, however, is only a few tenths of a millimeter per year, too small to matter for most applications.

3.4. A 13-Station Bootstrap Model for Caribbean Plate Motion

Based on the possibility that the velocities for sites BARB and ROJO are biased by elastic effects associated with locking of nearby faults, we eliminate the velocities at these sites and employ bootstrapping of the velocities for the remaining 13 sites to estimate an alternative Caribbean plate angular velocity vector. In this modified data set, stations from the western Caribbean (nine) outnumber stations from the eastern Caribbean (four). Angular velocity vectors derived from bootstrapping of this more limited set of velocities will thus yield models that are more biased toward fitting the western Caribbean GPS site velocities than is the case for our 15-station analysis. The two solutions thus constitute approximate end-members that can be compared to further assess the robustness of the Caribbean plate angular velocity vector.

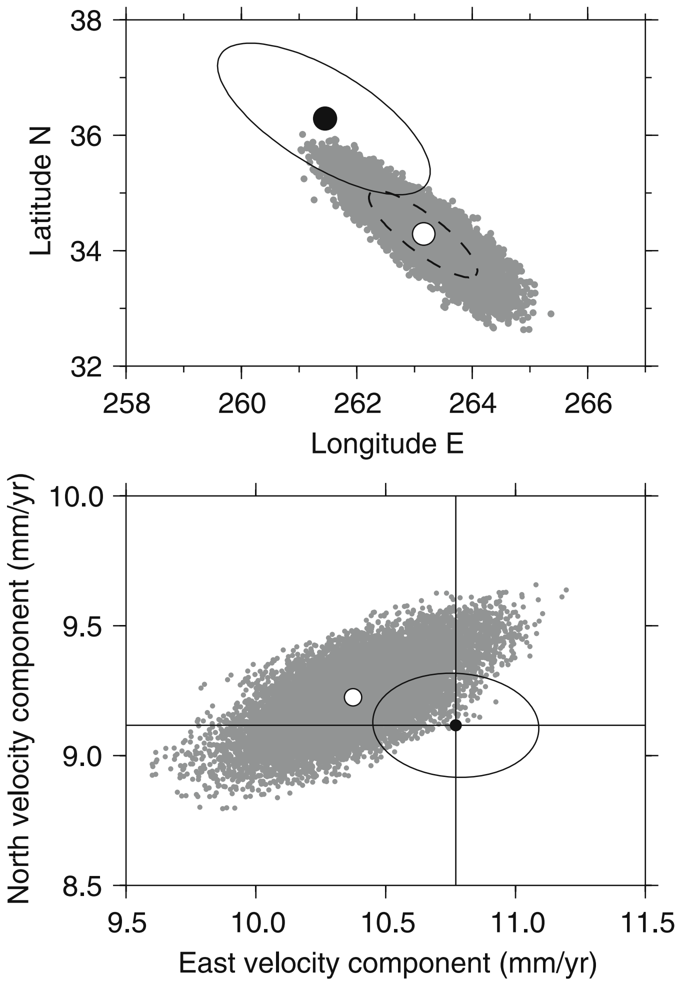

Figure 8. Upper: Thirteen-station bootstrap solution for Caribbean-ITRF2000 motion that omits velocities for sites BARB and ROJO. Open circle indicates mean location of bootstrap poles. Filled circle and ellipse show location of 15-station best-fitting pole and its two-dimensional, 1σ confidence ellipse. Individual bootstrap poles, shown with shaded circles, are derived by excluding one-by-one the velocities for sites AVES, CRO1, FSD0/1, SANA, and the eight Central American sites and inverting bootstrapped velocities for the remaining 12 sites. ITRF2000 is fixed. Lower: Velocities at central location on the Caribbean plate (15°N, 75°W) predicted by the CA-ITRF2000 13-station, bootstrap angular velocity vectors relative to the velocity predicted by the 15-station, best-fitting CA-ITRF2000 angular velocity vector (filled circle) and its formal two-dimensional, 1σ uncertainty. Open circle shows the linear velocity predicted by the mean bootstrapped angular velocity vector. The velocity origin (0, 0) is not shown.

Using the same bootstrapping procedure described in Section 3.3, 1000 velocity data sets were selected randomly from each of thirteen 12-station velocity subsets. Each of the 13,000 bootstrapped data sets was inverted to find its corresponding best-fitting angular velocity vector and the resulting solutions were averaged to determine a mean Caribbean-ITRF2000 angular velocity vector (Table 2). Variances and covariances that describe the uncertainties in the mean angular velocity vector were derived from the lengths and orientations of the three axes for the ellipsoid that encompasses 68.3% of the bootstrap solutions.

As is shown in Figure 8, bootstrapping the 13-station subset of velocities shifts the mean pole location to the southeast by 2.4 angular degrees and predicts motion that is 0.2 mm yr^{-1} slower and 1.4° degrees CCW from that predicted by the 15-station best-fitting model. The velocity difference slightly exceeds the prediction uncertainty of the 15-station, best-fitting Caribbean plate angular velocity vector (shown in Fig. 7) but is small in relationship to the tectonic signals being investigated around the margins of the Caribbean plate. Uncertainties in our determination of the Caribbean plate geodetic reference frame are thus not likely to constitute a limiting factor in studies of circum-Caribbean tectonics.

3.5. Testing for East-West Intraplate Deformation

We next employ the station velocities described in Section 3.4 to test for deformation within the Caribbean plate. The GPS stations available to us are mainly found at the far eastern and western ends of the Caribbean plate (Fig. 1) and are thus well located to test for the existence and magnitude of east-to-west intraplate deformation.

We begin by testing for deformation proposed by Mauffret and Leroy (1999), who estimate that the Beata Ridge has accommodated 9 ± 1.5 mm yr^{-1} of shortening since the early Miocene (23 Ma) based on their interpretation of marine seismic profiles from the eastern edge of the Beata Ridge. We tested for the proposed shortening by adding equal amounts of eastward motion to the velocities of sites located east of the Beata Ridge and westward motion to the velocities of sites west of the Beata Ridge. If any east-to-west shortening (or extension) occurs across one or more structures in the plate interior, then adding east-to-west deformation of the opposite sense to the velocities of sites that span the deforming zone will cancel some or all of the real deformation. The least-squares fit of a best-fitting angular velocity to GPS site velocities that are suitably corrected for any active shortening or extension should thus improve relative to the fit for the original, uncorrected GPS site velocities. Alternatively, if no deformation occurs, then imposing progressively larger east-west extension or shortening on the existing site velocities will yield progressively larger misfits for a best-fitting angular velocity vector. We use the F-ratio test to determine whether changes in the least-squares fit for different assumed amounts of east-west deformation are significant at a predefined confidence level. Our analysis thus establishes a rigorous upper bound on how much deformation could be occurring without rising above the detection threshold of the available GPS site velocities.

Figure 9 shows the least-squares fits to the 15 Caribbean site velocities for a series of models that impose progressively faster east-to-west extension or shortening across the plate interior. Relative to the least-squares fit to the original, unmodified GPS site velocities, the fit improves by ~5% for models that impose

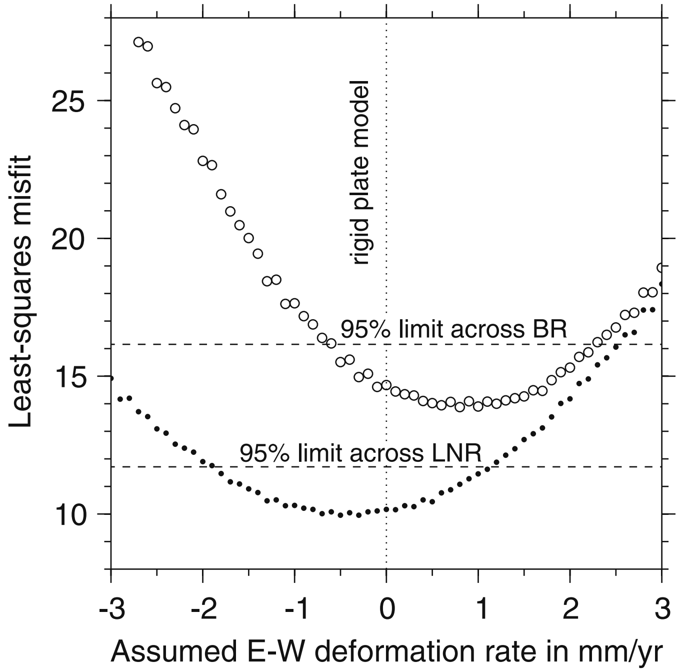

Figure 9. Comparison of least-squares misfits to GPS site velocities as a function of assumed rates of east-to-west extension (negative rates) or shortening (positive rates) across the Beata Ridge (BR) and Lower Nicaragua Rise (LNR). See text for description of how the assumed deformation is imposed on the raw GPS site velocities. Open circles show least-squares misfits for models that separate the 15 site velocities into groups east and west of the Beata Ridge; solid circles use the same velocities, but exclude site SANA located in the Lower Nicaragua Rise. Shaded region indicates the range of rates for assumed east-west plate deformation that do not increase the misfit at more than the 95% confidence level relative to the best-fitting model. The least-squares values associated with the 95% cutoff are determined using an *F*-ratio test for 1 versus 2*N-3-1 degrees of freedom, representing the number of north and east velocity components for *n* sites reduced by four adjustable parameters, three of which specify the best-fitting angular velocity and the fourth of which specifies the assumed east-west deformation rate.

as much as 1 mm yr^{-1} of shortening to the site velocities. The improvement in fit is not significant at any reasonable confidence level, indicating that shortening is not required. Overall, models that impose east-to-west plate shortening faster than ~2.5 mm yr^{-1} or extension faster than 0.5 mm yr^{-1} fit the data less well than for an assumed rigid plate at the 95% confidence level. Present-day shortening at rates as fast as the 9 ± 1.5 mm yr^{-1} rate is thus inconsistent with our GPS station velocities at high confidence levels.

We also tested the Holcombe et al. (1990) hypothesis that diffuse east-west extension of the Lower Nicaraguan Rise occurs in response to northeast-directed shear along its bounding escarpments. Doing so required only a minor modification to the above procedure; namely, we excluded the velocity for site SANA, which is located within the zone of diffuse deformation proposed by Holcombe et al. A model that corrects the GPS site motions for 0.5 mm yr^{-1} of east-west extension yields the best fit to the 14 remaining site velocities (Fig. 9), but fails to fit our station velocities significantly better than a simpler rigid plate model. The GPS velocities impose upper limits (at 95%) of 2 mm yr^{-1} of extension and 1 mm yr^{-1} of shortening for E-W oriented deformation across the Lower Nicaraguan Rise.

Our simple numerical experiments do not exclude more complex models of intraplate deformation in which, for example, deformations across the Beata Ridge and Lower Nicaragua Rise are nearly equal in magnitude, but opposite in sense, thereby canceling any integrated E-W directed deformation at the plate scale. The sparse distribution of sites in the plate interior unfortunately prevents us from testing more complex models.

4. DISCUSSION AND FUTURE WORK

The results reported in this paper have several useful implications. The eight new velocities from apparently stable areas of Honduras and Nicaragua allow for stronger tests of the model robustness than was previously possible. A variety of evidence indicates that our estimate of Caribbean plate motion is robust with respect to the 15 site velocities that are used to derive the best-fitting angular velocity vector and their estimated uncertainties. For example, removing any single site velocity and inverting the remaining velocities and their formal errors results in a maximum change of only 0.5 mm yr^{-1} and 0.4° in the motion estimated at a site in the plate interior (Fig. 7). Bootstrapping the velocities to sample a wider range of velocity weighting schemes confirms the apparent robustness of the solution, with estimated plate velocities that differ from the best-fitting solution by no more than 0.6 mm yr^{-1} and 1.7° (Fig. 7).

Two additional measures of the solution robustness reinforce this conclusion. The Swan Islands transform fault west of the Cayman spreading center (Fig. 2) is a narrow, seismically active fault that separates the Caribbean and North America plates. SeaMARC II multibeam mapping of this fault yields well-determined azimuths (Rosencrantz and Mann, 1991) that can be used to test the accuracy of geodetic estimates of Caribbean–North America plate motion. Our best-fitting Caribbean–North America plate angular velocity vector predicts slip directions that are only 2° clockwise and 2° counterclockwise from the measured azimuths at two locations where the fault has an easily interpreted trace (Fig. 3), insignificantly different within the uncertainties.

Our model predictions can also be compared to those of previous geodetic models, although such comparisons are less useful for validating model accuracy given that all published GPS-based models of Caribbean–North America plate motion are derived in part from significantly overlapping sets of GPS site velocities (e.g., Dixon et al., 1998; DeMets et al., 2000; DeMets, 2001; Sella et al., 2002). Nonetheless, the Caribbean–North America plate velocity predicted by our new angular velocity vector at the geographic center of the Caribbean plate, 19.7 ± 0.4 mm yr^{-1} toward N75.6°E ± 0.9° (1-σ), differs insignificantly from the 19.2 mm yr^{-1}, N74.9°E velocity predicted by the Sella et al. (2002)

model. Differences between the present model and that published by DeMets (2001) are also small (see dashed line in Fig. 3).

The new Central American GPS velocities have several important regional and local tectonic implications. Seven of the eight site velocities are misfit by <1.9 mm yr^{-1} by our best-fitting, 15-station model (Fig. 3), which indicates that significant areas of eastern Central America move with the Caribbean plate interior. The similarity of the motions of sites located on either side of the prominent but aseismic Guayupe fault suggests that this fault is inactive. In contrast, progressively faster westward motion of 3 ± 1 mm yr^{-1} at TEGU and 8 ± 1 mm yr^{-1} (Fig. 6) at GUAT west of central Honduras indicates that distributed east-west extension occurs in areas of western Central America. The result is consistent with geologic and seismic observations of east-west extension across central and western Honduras and Guatemala (Manton, 1987; Guzman-Speziale, 2001).

Finally, simple, but rigorous numerical experiments with the GPS site velocities indicate that any east-to-west deformation across the Beata Ridge and Lower Nicaraguan Rise is unlikely to exceed 2 mm yr^{-1} and within the uncertainties is zero (Fig. 9). The kinematic evidence for insignificant east-to-west deformation agrees with results reported by Driscoll and Diebold (1998), who conclude that marine seismic data from the Beata Ridge do not require the occurrence of significant contraction across this structure since the Miocene. If such contraction has occurred, as suggested by Mauffret and Leroy (1999), our results suggest that it has now ceased.

Our results suggest useful strategies for future efforts to further improve estimates of Caribbean plate motion. One or more continuous GPS sites in eastern Honduras and/or Nicaragua would contribute geographically unique and well-constrained information about Caribbean plate motion. Long-term monitoring of the east-west length of a baseline between such sites and the existing continuous GPS station on St. Croix Island (CRO1) in the eastern Caribbean would provide a stronger basis for detecting any east-to-west intraplate deformation. Tectonic biases in the motions of sites in southern Hispaniola and Jamaica (Figs. 5–7) make these islands poor targets for monitoring the motion of the plate interior unless suitable corrections for elastic strain accumulation are undertaken. Future occupations of AVES and SANA are clearly warranted in light of their locations in the plate interior, and site velocities from the Lesser Antilles volcanic islands are needed to establish whether some islands move with the plate interior.

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