GPS estimate of relative motion between the Caribbean and South American plates, and geologic implications for Trinidad and Venezuela

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ABSTRACT

Global Positioning System (GPS) data from eight sites on the Caribbean plate and five sites on the South American plate were inverted to derive an angular velocity vector describing present-day relative plate motion. Both the Caribbean and South American velocity data fit rigid-plate models to within ±1–2 mm/yr, the GPS velocity uncertainty. The Caribbean plate moves approximately due east relative to South America at a rate of ~20 mm/yr along most of the plate boundary, significantly faster than the NUVEL-1A model prediction, but with similar azimuth. Pure wrenching is concentrated along the approximately east-striking, seismic, El Pilar fault in Venezuela. In contrast, transpression occurs along the 068°-trending Central Range (Warm Springs) fault in Trinidad, which is aseismic, possibly locked, and oblique to local plate motion.

Keywords: plate tectonics, neotectonics, Global Positioning System (GPS), Caribbean, South America, Trinidad, Venezuela, seismic hazard.

INTRODUCTION

The relative motion between the Caribbean and South American plates is poorly resolved in existing plate kinematic models (DeMets et al., 1990, 1994; Stein et al., 1993; Deng and Sykes, 1995) and neotectonic models based mainly on continental geology (Robertson and Burke, 1989; Speed, 1985; Algar and Pindell, 1994; Flinch et al., 1999). In NUVEL-1A (DeMets et al., 1990, 1994), the most precise geologic model of global plate motion currently available, the Caribbean–South American relative angular-velocity (Euler) vector is the most poorly determined of all global plate pairs; consequently, it has the highest uncertainty. Earthquakes in the Caribbean–South American plate-boundary zone provide some directional plate-motion information, but large upper-crustal events are few and unevenly distributed, whereas more numerous smaller events give very scattered results (Russo et al., 1993), reflecting a mix of plate motion as well as local tectonic processes (Deng and Sykes, 1995). Furthermore, transtension, transpression, and pure wrenching have all been proposed as the current deformation styles within the Caribbean–South American plate boundary zone.

We report the first geodetic estimate of Caribbean–South American relative motion based on data from eight Global Positioning System (GPS) sites on the Caribbean plate and five GPS sites on the South American plate. Velocity residuals and χ^2 misfits are used to test for Caribbean plate rigidity and possible plate-edge effects. We compare the results with previous plate kinematic models and large earthquake slip vectors and discuss geologic implications.

DATA ANALYSIS

Continuous and campaign-style GPS data were analyzed at the University of Miami following Dixon et al. (1997). We used the GIPSY software developed at the Jet Propulsion

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TABLE 1. SITE LOCATIONS, OBSERVED AND RESIDUAL VELOCITIES

	Lat (°N)	Long (°E)	Observed[*] North	Observed[*] East	Residual[†] North	Residual[†] East
Caribbean four-site rigid-plate model; χ_v^2 misfit = 1.47						
AVES (Aves Is.)	15.67	−63.62	11.5 ± 0.9	13.2 ± 2.1	0.4	1.2
CRO1 (St. Croix)	17.76	−64.58	10.9 ± 0.5	10.5 ± 0.8	0.2	−0.5
ROJO (D.R.)	17.90	−71.67	6.2 ± 0.9	11.5 ± 1.9	−1.7	1.0
SANA (San Andres Is.)	12.52	−81.73	4.8 ± 0.9	14.1 ± 1.2	1.2	1.2
Caribbean eight-site rigid-plate model; χ_v^2 misfit = 0.94						
AVES (Aves Is.)	15.67	−63.62	11.5 ± 0.9	13.2 ± 2.1	0.4	1.2
BARB (Barbados)	13.09	−59.61	13.0 ± 1.1	14.2 ± 2.1	0.4	0.9
CRO1 (St. Croix)	17.76	−64.58	10.9 ± 0.5	10.5 ± 0.8	0.2	−0.5
ISAB (P.R.)	18.46	−67.05	9.3 ± 1.4	11.1 ± 2.0	−0.4	0.6
PUR3 (P.R.)	18.46	−67.07	9.7 ± 0.9	7.7 ± 1.6	0.0	−2.8
ROJO (D.R.)	17.90	−71.67	6.2 ± 0.9	11.5 ± 1.9	−1.7	1.0
SANA (San Andres Is.)	12.52	−81.73	4.8 ± 0.9	14.1 ± 1.2	1.2	1.2
TDAD[§] (Trinidad)	10.68	−61.40	10.7 ± 1.4	15.9 ± 3.2	−1.3	1.6
South American rigid-plate model; χ_v^2 misfit = 0.77						
ASC1 (Ascension Is.)	−7.95	−14.41	8.8 ± 1.5	−5.3 ± 2.4	−0.6	0.5
BRAZ (Brazil)	−15.95	−47.88	11.3 ± 1.1	−6.9 ± 2.2	0.4	−2.2
FORT (Brazil)	−3.88	−38.43	11.5 ± 0.9	−6.7 ± 1.6	0.6	−1.6
KOUR (Fr. Guyana)	5.25	−52.81	10.0 ± 0.8	−3.5 ± 1.5	−0.9	1.7
LPGS (Argentina)	−34.91	−57.93	11.0 ± 1.2	−1.6 ± 2.1	0.3	1.2

Note: D.R. = Dominican Republic; P.R. = Puerto Rico.

[*] Velocites (mm/yr) relative to ITRF-97.

[†] Residual velocities (mm/yr), observed minus predicted, based on best fit ITRF-97 angular velocity vectors (Table 2).

[§] TDAD is northern Trinidad triangulation station 0069; southern Trinidad triangulation station 0115 at 10.10°N, −61.66°E, discussed in text but not used in rigid-plate models, has velocities (mm/yr) relative to ITRF-97 of 8.1 ± 1.2 (north), and 2.0 ± 2.7 (east).

Laboratory (JPL) and JPL satellite ephemeris and clock files (Zumberge et al., 1997). We first derived site velocities in the global ITRF-97 reference frame (1997 International Terrestrial Reference Frame; Boucher et al., 1999) (Table 1). Site velocity errors were estimated following Mao et al. (1999), as modified by Dixon et al. (2000). Best-fitting angular-velocity vectors describing motion of the Caribbean and South American plates relative to ITRF-97 were derived by a formal inversion procedure (Ward, 1990; Mao, 1998). The ITRF-97–referenced angular-velocity vector for the Caribbean plate is defined by using a total of six campaign and two continuous sites (Table 1, Fig. 1). To test for possible edge effects, such as that due to elastic-strain accumulation on locked plate-boundary faults, following Dixon et al. (2000) and De Mets et al. (2000), we also derived a vector based on a more conservative subset of four plate-interior sites (Table 1). For the South American plate, we used four continuous sites on the presumably stable continental shield and platform and one continuous site (ASC1) in the southeastern Atlantic on Ascension Island, west of the Mid-Atlantic Ridge (Table 1, Fig. 1). The ITRF-97–referenced Caribbean and South American angular-velocity vectors were then subtracted to derive new angular velocity vectors describing the motion of the Caribbean plate relative to stable South America (Table 2).

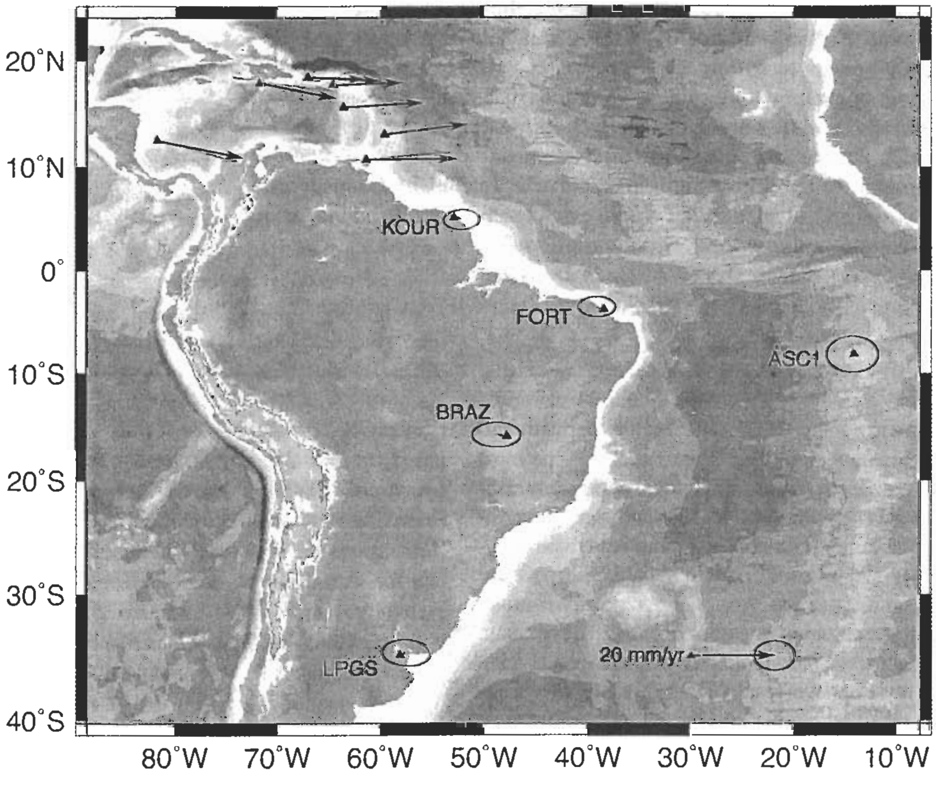

Figure 1. Map showing locations and motions (observed—black; predicted—red) of sites on Caribbean and South American plates relative to the stable South American reference frame defined in this study. Error ellipses and site names omitted on Caribbean plate for clarity. Small black arrows and error ellipses indicate statistically insignificant residual South American site motions. See Table 1 for site names and locations.

RIGIDITY OF THE CARIBBEAN AND SOUTH AMERICAN PLATES

Dixon et al. (1996) used residuals between GPS-determined velocities and those predicted by a rigid-plate model to investigate the rigidity of the North American plate interior. In that study, the average rate residual for eight North American stations was 1.3 mm/yr. Using a larger data set and longer time series, DeMets and Dixon (1999) determined an average rate residual of 1.0 mm/yr for 16 stable North America stations. These residuals probably reflect the magnitude of GPS velocity errors, rather than true nonrigid plate processes. In the later study, the velocity errors were independently estimated following Mao et al. (1999), and χ^2 per degree of freedom (χ_ν^2), a parameter describing the goodness-of-fit of the data to the rigid-plate model, was approximately unity, as expected if the model is appropriate and the errors are realistic. We applied the same velocity error model and the same rigidity tests to our Caribbean and South American data sets. The mean rate residuals are, respectively, 1.3 mm/yr for the four-site Caribbean plate model (χ_ν^2 = 1.47), 1.5 mm/yr for the eight-site Caribbean plate model (χ_ν^2 = 0.94), and 1.6 mm/yr for the South American plate model (χ_ν^2 = 0.77). These re-

TABLE 2. ANGULAR-VELOCITY VECTORS DESCRIBING RELATIVE MOTION BETWEEN THE CARIBBEAN AND SOUTH AMERICAN PLATES

	Lat (°N)	Long (°E)	ω (°/m.y.)	Error ellipse*			σ_ω (°/m.y.)
				σ_{max}	σ_{min}	ζ_{max}	
This study							
four-site Caribbean	52.1	−65.9	0.271	7.5	2.2	−4.0	0.030
eight-site Caribbean	51.5	−65.7	0.272	6.1	1.9	−8.6	0.023
NUVEL-1A†	50.0	−65.3	0.18	14.9	4.3	−2.0	0.03
NUVEL-1 (alt.)§	63.1	−15.2	0.13	—	—	—	—
Deng and Sykes#	52	−81	—	—	—	—	—

*ζ_{max} is orientation of long axis, degrees clockwise from north. Axes are two-dimensional one standard error; for 95% confidence, multiply by 1.7.

†DeMets et al. (1994).

§DeMets et al. (1990); alt. = alternative vector derived without using Lesser Antilles slip vectors (uncertainties not given).

#Deng and Sykes (1995) (uncertainties and rate not given).

siduals are approximately the same magnitude as our velocity-error estimates (Table 1) and χ_ν^2 is ~1; these results suggest that single-rigid-plate models are appropriate for both the Caribbean and South American plates.

The average GPS velocity errors for the South American sites, which are semipermanent stations that have been operating continuously for at least several years are small, ±1–2 mm/yr (Table 1). Those for the Caribbean sites, which include campaign sites (AVES, ISAB, ROJO, SANA, TDAD) that have been occupied periodically, and continuous stations (CR01, BARB, PUR3) similar to those operating in South America but with slightly shorter time spans, are equally small (Table 1). These new high-precision Caribbean velocity data do not support models involving two or more Caribbean "subplates" (e.g., Dewey and Pindell, 1985; Mauffret and Leroy, 1997). The small uncertainties and residuals permit semi-independent motion between blocks or microplates only up to about 2 mm/yr.

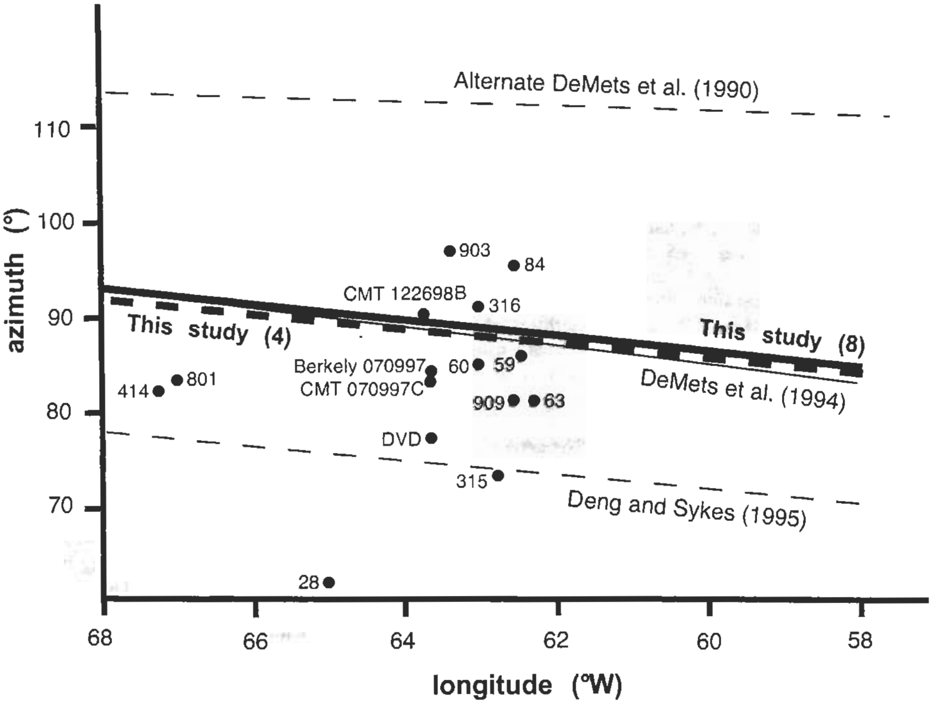

Figure 2. Predicted Caribbean–South American velocity azimuth (degrees clockwise from north) along plate boundary zone in northern South America and Trinidad at 10.5°N from this (thick lines; solid line is for eight-site Caribbean rigid-plate model; dashed line is for four-site Caribbean rigid-plate model) and previous (thin lines) studies. Four-site and eight-site Caribbean rigid-plate models both predict constant velocity magnitude of ~20 mm/yr across this region. Dots are slip-vector azimuths for large, upper crustal earthquakes. Numbers are event numbers in Deng and Sykes (1995) Table 1. DVD is slip vector from Doser and Van Dusen (1996) for 1929 magnitude 6.9 Cumana earthquake. Harvard CMT and Berkeley determinations for July 9, 1997, magnitude 6.8 Cariaco event and Harvard CMT determination for a December 26, 1998, event are labeled. Model labeled "Alternate DeMets et al. (1990)" omits earthquake slip vectors in Lesser Antilles. Note that Central Range fault segment of plate boundary zone in Trinidad (~61°–62°W) is aseismic, whereas El Pilar fault segment in Venezuela (~62°–65°W) is seismically active.

Because the four-site and eight-site Caribbean plate models give nearly identical results (Table 1), elastic effects at the four Caribbean "edge" sites must be small. This suggestion is consistent with independent mechanical models that estimate the magnitude of elastic-strain accumulation. For example, a simple elastic half-space model (Savage, 1983) for strain accumulation along the Lesser Antilles subduction-zone interface between the Caribbean and South American plates, assuming 50% locking, predicts elastic velocity effects at BARB (Table 1, Fig. 1) that are less than 1 mm/yr. This result is probably an upper limit, because the 50% plate coupling assumed is a maximum value given the relatively old age of subducting South American oceanic lithosphere at this location (Stein et al., 1982).

COMPARISON OF ANGULAR-VELOCITY VECTORS AND GEOLOGIC IMPLICATIONS

Our new Caribbean–South American angular-velocity vectors and, for comparison, those of DeMets et al. (1994) and Deng and Sykes (1995), are presented in Table 2 and Figure 2. The new Caribbean–South American angular velocity vectors based on four and eight Caribbean sites are equivalent within uncertainties. In the following discussion, we use the vector based on the larger data set, because it has approximately the same mean rate residual and a significantly lower χ_ν^2 misfit (Table 2).

Similar to the findings of Dixon et al. (1998) on Caribbean–North American plate motion, the local plate motions predicted by our new angular-velocity vector are faster than those predicted by NUVEL-1A. However, NUVEL-1A and our new vector predict motions that are almost identical in azimuth (Fig. 2). For example, at a location on the plate boundary in Trinidad (lat 10.4°N, long 61.2°W, on the Central Range fault; Weber et al., 1999), we predict that the Caribbean plate moves 20 ±3 mm/yr in a direction 086° ±2°, compared to the NUVEL-1A prediction of 13.5 mm/yr at 086°. At this location, the Central Range fault has an average strike of 068°. The high obliquity between the predicted local plate motion and observed strike of the active fault provides a simple explanation for the transpressive structural features, such as recent uplift and folding and thrust faulting, that are well developed and apparently active in the Central Range.

We updated the upper-crustal earthquake slip-vector data set of Deng and Sykes (1995) with Harvard centroid moment tensor (CMT) and Berkeley focal mechanisms for two additional events, and a determination from a historic event (Doser and Van Dusen, 1996). These data provide independent azimuth information with which to evaluate our new angular-velocity vector, and they agree with it quite well (Fig. 2).

Robertson and Burke (1989) used geologic data to infer that the Caribbean–South American plate boundary zone is several hundred kilometers wide in Trinidad and along northern South America. Weber et al. (1999) compared 1901–1903 triangulation data to 1994–1995 GPS data at 23 sites in Trinidad and determined that the Central Range (Warm Springs) fault is the major active strike-slip fault in Trinidad, albeit aseismic and possibly locked. Data from two campaign GPS sites in Trinidad provide additional insight. Site TDAD (Table 1) is roughly 35 km north of the Central Range fault, and moves, within errors, at the full Caribbean plate rate (north residual = −1.3 mm/yr, east residual = 1.6 mm/yr). On the other hand, a GPS site in southern Trinidad, about 60 km away (triangulation station 0115), moves 14 ±3 mm/yr slower toward the east (recall that the predicted plate motion is 20 ±3 mm/yr). These observations suggest that the Central Range fault currently accommodates most Caribbean–South American plate motion in Trinidad, and that the plate-boundary zone may be narrower than previously thought.

Our new angular-velocity vector predicts motion directed 090° ±2° along the seismically active approximately east-striking El Pilar fault in Venezuela (Fig. 2) and pure dextral wrenching as the current deformation style there. In contrast, we infer that transpression is active in Trinidad, where the active Central Range fault is highly oblique to plate motion. That 14 ±3 mm/yr of motion is taken up aseismically across the Central Range fault, both today and historically, implies that this fault may be locked and could constitute a seismic hazard. The general eastward relative Caribbean plate motion we observe compares favorably with the strong approximately east-trending mantle fabric in the plate-boundary zone imaged by Russo et al. (1996) with a seismic-shear-wave-splitting experiment. The presence of a pervasive mantle fabric with this orientation probably indicates that the Caribbean plate has moved in the general direction we observe today for a geologically significant period of time. This inference is supported by the observation that the current plate-motion azimuth measured with GPS is essentially identical to the NUVEL-1A result, which averages over ~3 m.y. In addition, it is consistent with the observation that a probable key boundary condition for Caribbean motion, North America–South America motion, has been steady for at least the past 10 m.y. (e.g., Dixon and Mao, 1997).

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