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 $\chi^2$ 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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Geology; January 2001; v. 29; no. 1; p. 75–78; 2 figures; 2 tables.
TABLE 1. SITE LOCATIONS, OBSERVED AND RESIDUAL VELOCITIES

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

Note: D.R. = Dominican Republic; P.R. = Puerto Rico.
*Velocities (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).

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 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 \( \chi^2 \) per degree of freedom (\( \chi^2 \)), 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 (\( \chi^2 = 1.47 \)), 1.5 mm/yr for the eight-site Caribbean plate model (\( \chi^2 = 0.94 \)), and 1.6 mm/yr for the South American plate model (\( \chi^2 = 0.77 \)). These results indicate that the Caribbean plate is rigidly moving with respect to the stable South American plate, and that the South American plate is also rigidly moving with respect to the stable South American plate.
TABLE 2. ANGULAR-VELOCITY VECTORS DESCRIBING RELATIVE MOTION BETWEEN THE CARIBBEAN AND SOUTH AMERICAN PLATES

<table>
<thead>
<tr>
<th>Lat (°N)</th>
<th>Long (°E)</th>
<th>ω (°/m.y.)</th>
<th>Error ellipse*</th>
<th>σzmax</th>
<th>σzmin</th>
<th>σzmax</th>
</tr>
</thead>
<tbody>
<tr>
<td>This study</td>
<td></td>
<td>four-site Caribbean</td>
<td>52.1</td>
<td>−65.9</td>
<td>0.271</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td>eight-site Caribbean</td>
<td>51.5</td>
<td>−65.7</td>
<td>0.272</td>
<td>6.1</td>
<td>1.9</td>
</tr>
<tr>
<td>NUVEL-1A</td>
<td>50.0</td>
<td>−65.3</td>
<td>0.18</td>
<td>14.9</td>
<td>4.3</td>
<td>−2.0</td>
</tr>
<tr>
<td>NUVEL-1 (alt.);6</td>
<td>63.1</td>
<td>−15.2</td>
<td>0.13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deng and Sykes,6</td>
<td>92</td>
<td>−61</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

The residuals are approximately the same magnitude as our velocity-error estimates (Table 1) and χ² 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.

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 χ² 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...
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We are grateful to the International Geodynamics Service (IGS) and other members of the international geodetic community who generously make high-quality data from permanent GPS stations publicly available in a timely manner. We thank Keith Rowley, Lloyd Lynch, Previn Kennedy, Murchison Pierre, the Decoteau family, Wayne and Stephen Williams, Andrew McCarthy, and many others who helped us make GPS campaign measurements. This work was supported by NASA’s Dynamics of the Solid Earth Program, Conicet (Project S1-97001365), the Caltech President’s Fund, and National Science Foundation Postdoctoral Fellowship EAR-9404214 and a Conoco Young Professor’s Award to Weber, who thanks Judith Hannah, Keith James, Tomas Villamil, and James Deckelman for logistical support.

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