4-2006

Is There a Northern Lesser Antilles Forearc Block?

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Received 22 November 2005; revised 6 February 2006; accepted 3 March 2006; published 12 April 2006.

[1] A systematic discrepancy exists between slip vectors of thrust fault earthquakes at the Lesser Antilles trench (LAT) and the predicted direction of North American-Caribbean convergence. A possibility has been that the discrepancy resulted because neither was well constrained. Estimating Caribbean motion has been challenging owing to the limited data along the plate's complex boundaries. Similarly, earlier studies had few slip vectors because interplate thrust events are infrequent. To address these difficulties, we estimate a new Caribbean-North America Euler vector using recently available GPS data from sites in the presumably stable interior of the Caribbean, and compare the predicted velocities to a larger set of slip vectors. The discrepancy persists, suggesting the northern Lesser Antilles forearc (NLAF) moves as a distinct entity from both the Caribbean and North America. For simplicity, we treat its motion as a coherent block, but because GPS sites are not within the NLAF, distributed deformation is also possible. Although there is no geologic evidence for the boundaries of the presumed NLAF block, GPS data show that the motions of Martinique, Barbados, and Trinidad are similar to that of the Caribbean, suggesting that none are on the NLAF block, and the southern LAT is weakly coupled.
Citation: López, A. M., S. Stein, T. Dixon, G. Sella, E. Calais, P. Jansma, J. Weber, and P. LaFemina (2006), Is there a northern Lesser Antilles forearc block?, *Geophys. Res. Lett.*, *33*, L07313, doi:10.1029/2005GL025293.

1. Introduction

[2] Determining how the Caribbean (CA) plate moves with respect to the neighboring North America (NA) and South America (SA) plates has been a major challenge. Geologic plate motion models using seafloor magnetic anomaly rates, transform fault azimuths and slip vectors faced difficulties due to sparse data. The only rates come from the Cayman Spreading Center (CSC), and seismicity at the eastern boundary is low due to slow convergence. Moreover, the boundary geometry is still unclear, since the CA's north and south boundaries are complex deformation zones and it is uncertain where the CA-NA-SA triple junction lies.

[3] As a result, CA plate motion is poorly constrained in models like NUVEL-1 [*DeMets et al.*, 1994]. This lack of knowledge manifested itself in the Lesser Antilles (LA). *Stein et al.* [1988] noted that the discrepancy between the ~2 cm/yr of CA-NA motion found by *Jordan* [1975] based on the CSC spreading rate, and the ~4 cm/yr found by *Sykes et al.* [1982] using slip vectors at the LA trench (LAT) and the length of the Wadati-Benioff zone, resulted from the data used. Models based on LAT slip vectors misfit CSC rates and vice versa. This discrepancy might reflect either or both of two biases. First, the Cayman rate might not reflect full NA-CA motion due to deformation within the Northern CA plate boundary zone (NCPBZ). Second, the LAT slip vectors might not reflect NA-CA motion if the LA forearc moves separately from both NA and CA.

[4] GPS geodesy yielded new insights into NA-CA motion at the NCPBZ [*Dixon et al.*, 1998; *Mann et al.*, 2002; *Calais et al.*, 2003] and is helping to address slip partitioning at the LAT. Here we revisit LA motions using a new NA-CA Euler vector derived from an improved GPS data set, which has additional sites with longer time series. We compare these data to a larger slip vector data set to suggest a possible forearc sliver along the northern portion of the LA.

2. Caribbean Plate Motion

[5] We estimated CA plate motion using GPS sites (Figure 1 and Table 1) AVES (Aves Island), BARB (Barbados), CORN and PUEC (Nicaragua), CRO1 (St.Croix), FSD0 and FSD1 (Martinique), SANA (San Andrés Island), and TDAD (Trinidad).

[6] We processed the data in the IGSb00 (a pure GPS version of the ITRF2000) reference frame [*Ray et al.*, 2004] using GIPSY software [*Zumberge et al.*, 1997] at the University of Miami and precise satellite orbits and clocks from JPL. Processing procedures followed *Sella et al.* [2002], and velocity uncertainties were estimated using the noise model from *Mao et al.* [1999]. Most sites have been episodically occupied. CRO1 and BARB are continuous, but BARB has been offline since 2001.

[7] Following *DeMets et al.* [2000], *Weber et al.* [2001], and *Sella et al.* [2002], we derived three Euler vectors with a combination of the sites in Table 1. We also formed hybrid Euler vectors by combining the GPS-derived velocities with two Swan Island transform faults (SITF) azimuths (stars in Figure 1) [*Rosencrantz and Mann*, 1991]. Caribbean Euler vectors and associated uncertainties in IGSb00 (Table 2) were derived by inverting the GPS data sets and a hybrid data set of GPS data plus the two SITF azimuths.

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0094-8276/06/2005GL025293

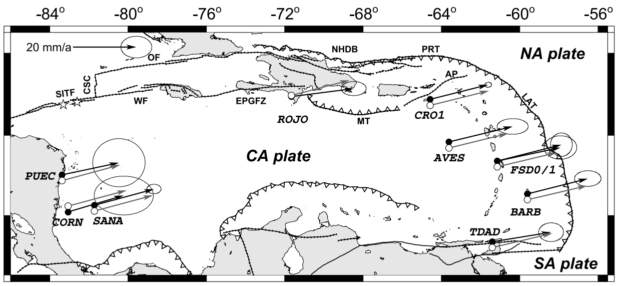

Figure 1. Regional tectonic map. Black circles and vectors with 2σ error ellipse are velocities of sites in a NA reference frame. Open circles with gray vectors (offset for clarity) are velocities predicted by our 9-site GPS-only CA-NA Euler vector. ROJO, previously considered as a stable CA site, was not used in the inversions. AP-Anegada Passage, CSC-Cayman Spreading Center, EPGFZ-Enriquillo-Plantain Garden Fault Zone, LAT-Lesser Antilles Trench, MT-Muertos Trough, NHF-Northern Hispaniola Fault, OF-Oriente Fault, PRT-Puerto Rico Trench, SITF-Swan Island Transform Fault.

[8] To test how the Euler vector depended on the sites whose velocities we inverted to estimate it, we compared several solutions. We first defined the stable CA plate using the three sites (first three in Table 1) least likely to be significantly affected by plate boundary zone processes. However, after processing the three additional sites with sufficiently long time series and finding agreement between their velocities and those of the three original sites, we also treated them as part of the stable plate, i.e., unaffected by plate boundary deformation. The last three sites of Table 1 were added subsequently to analyze how the pole would change to the 6-site solution. Inclusion of relatively new sites in eastern Nicaragua, CORN (Corn Island) and PUEC (Puerto Cabezas), yielded results in agreement with SANA. We also included TDAD into the solution, despite its location near the boundary with the SA plate.

[9] Because the CA plate is primarily oceanic, most GPS sites are along its complex boundaries, making it difficult to assess whether a site velocity misfits a model derived for the entire plate because the site is in a boundary zone or because the model is biased by deformation in the plate's interior [*Driscol and Diebold*, 1998]. At least for TDAD and the LA, elastic strain accumulation effects due to the seismic cycle are probably not significant. Comparisons of GPS site velocities with those predicted by previous plate models find that boundary segments near TDAD and at the LA are only weakly coupled [*Weber et al.*, 2001; *Przybylski et al.*, 2005, manuscript in preparation, 2006].

[10] Results from inverting the hybrid data were essentially the same as from the GPS data alone and since all 3 pure GPS solutions yielded good approximations to the SITF azimuths, we opted to use these only. To obtain velocities in a NA reference frame, we used an improved version of the REVEL [*Sella et al.*, 2002] NA Euler vector, in which the selected 89 sites in IGSb00 are presumably free of glacial-isostatic adjustment (G. F. Sella, personal communication, 2005). The Euler vectors overlap at the 2σ level from those of *Sella et al.* [2002] and *Kreemer et al.* [2003] and differs significantly from the hybrid solution of *DeMets et al.* [2000]. (The latter's Table 1 contains a typographical error; the ϕ of the CA-IT Euler vector should be 265.9° instead of 275.9°). Similarly, we obtained a CA-SA Euler vector by substracting an 11 site SA Euler vector in IGSb00 (G. F. Sella, personal communication, 2005), which yielded results consistent with previous studies [*Weber et al.*, 2001; *Sella et al.*, 2002; *Kreemer et al.*, 2003].

[11] *DeMets et al.* [2000] suggested an upper-bound to the internal deformation of the CA plate of 4–6 mm/yr from the average misfit of 2 mm/yr of their hybrid model to the GPS velocities, in particular at western sites ROJO (Cabo Rojo, Dominican Republic) and SANA. We did not use ROJO in our analysis because doing so yields a noticeable misfit, perhaps reflecting boundary deformation along faults in the Sierra de Bahoruco ∼50 km north of ROJO. In contrast, the additional data does not indicate any misfit at SANA.

[12] Our improved data set yields mean rate residuals lower than found by *Weber et al.* [2001] and agrees with their suggestion of a single-plate model for the Caribbean. The 6-site solution yields a mean rate residual of 0.81 mm/yr with reduced chi square (χ^2_ν) value of 0.30. Adding the Nicaraguan sites and subsequently TDAD to the inversion, yields 0.90 mm/yr ($\chi^2_\nu = 0.22$), and 0.99 mm/yr ($\chi^2_\nu = 0.31$) for the 8-site and 9-site solutions, respectively.

Table 1. GPS Velocities in IGSb00[a]

Site ID	Lat., °N	Long., °E	ΔT, years	N	V_n, mm/yr	V_e, mm/yr
AVES	15.67	−63.62	3.87	2	13.0 ± 1.0	12.8 ± 2.00
SANA	12.53	−81.73	9.16	5	06.7 ± 0.6	12.2 ± 0.90
CRO1	17.76	−64.58	10.42	-[b]	12.4 ± 0.3	10.3 ± 0.40
BARB	13.09	−59.61	3.24	-[b]	14.3 ± 1.0	12.7 ± 1.70
FSD0	14.73	−61.15	5.47	2	13.2 ± 1.5	13.0 ± 2.10
FSD1	14.73	−61.15	5.46	2	14.1 ± 1.5	13.3 ± 1.40
CORN	12.17	−83.06	2.11	2	6.3 ± 2.5	11.0 ± 3.80
PUEC	14.04	−83.38	2.10	2	4.8 ± 3.1	10.8 ± 3.40
TDAD	10.68	−61.40	10.63	3	11.9 ± 1.2	12.9 ± 1.60

[a]ΔT Span of observations used. N number of occupations.
[b]Continuous GPS site.

Table 2. Euler Vectors for Plate Pairs[a]

Plate Pair	Model	Lat., °N	Lon., °E	ω	σ_1, deg.	σ_2, deg.	η, deg.	σ_ω
CA-IGSb00	6-site	37.4	−98.9	0.250	2.0	0.5	−57	0.009
	8-site	37.3	−98.8	0.251	1.7	0.4	−61	0.007
	9-site	37.6	−99.3	0.247	1.9	0.5	−62	0.008
CA-NA	6-site	75.5	−172.8	0.177	4.9	0.7	71	0.004
	8-site	75.1	−172.2	0.177	4.1	0.6	72	0.003
	9-site	75.2	−177.4	0.176	4.7	0.7	67	0.003
	RVL	75.5	−154.6	0.180	10.9	1.3	88	0.008
	D2k	64.9	−109.5	0.214	14.6	1.5	−35	0.030
CA-SA	6-site	57.1	−69.5	0.236	3.9	1.2	−17	0.009
	8-site	57.0	−69.5	0.237	3.7	1.1	−19	0.008
	9-site	57.6	−69.3	0.233	3.9	1.2	−17	0.009
	W01	51.5	−65.7	0.272	6.1	1.9	−8	0.023
	RVL	52.8	−66.3	0.267	5.4	1.4	−5	0.021

[a]9-site uses all sites in Table 1. 8-site excludes TDAD. 6-site excludes TDAD, CORN and PUEC. σ_1 and σ_2 are lengths of 2D, 1σ semi-major and semi-minor axes of Euler pole error ellipse. ω and σ_ω are in °/Myr. η is azimuth of semi-major axis σ_1 in degrees clockwise from north. RVL from *Sella et al.* [2002]. D2k from *DeMets et al.* [2000]. W01 is the 8-site Euler vector from *Weber et al.* [2001].

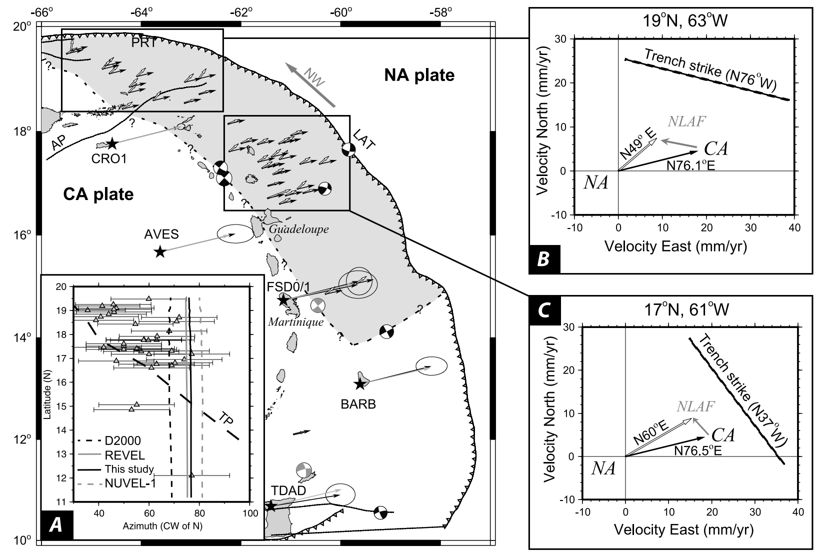

Figure 2. Slip partitioning and the possible NLAF block. Maps shows deviation of slip vectors (white arrows) from predictions (black arrows) of our 9-site CA-NA Euler vector. Black (0–20 km) and gray (20–40 km) strike-slip focal mechanisms are from the Harvard CMT catalog. (a) Azimuths of shallow thrust slip vectors (triangles) and predictions of various Euler vectors. TP = trench normal azimuth. D2000 from *DeMets et al.* [2000]. (b) and (c)Average SV azimuths (white vector) from two regions show misfit to predicted azimuth (black vector) at those locations, suggesting the presence of a block moving WNW with respect to CA.

[13] The velocities of TDAD, FSD0, FSD1, and BARB are similar in rates and azimuths to the models predictions. Hence, although the site geometry precludes testing them against a model derived only from sites within the plate interior, it appears that at least the southern half of the LA arc moves consistently with the CA plate.

3. Lesser Antilles Forearc Motion

[14] Comparison of the new GPS-derived plate motion directions to an updated slip vector data set at the LA trench shows that the discrepancy persists. We used all available shallow thrust events from the Harvard CMT catalog with T-axes plunge greater than 45° and depths shallower than 40 km. We assign the slip vectors a nominal uncertainty of 15°. We added the two slip vectors from *Sykes et al.* [1982] that are relevant to the area. Figure 2a shows how the slip vector azimuths differ from the predictions of the selected CA-NA Euler vectors.

[15] The slip vectors trend between the trench-normal and predicted convergence directions, an effect observed at other trenches where plate motion is oblique to the trench. This phenomena is attributed to slip partitioning, in which a forearc sliver moves separately from the overriding and subducting plates [*DeMets and Stein*, 1990; *McCaffrey*, 1992, 2002]. In such cases, because the slip vectors do not represent motion between the major plates, including them can bias a plate motion model [*DeMets et al.*, 1994]. In the limiting case of pure slip partitioning, pure thrust faulting occurs at the trench, and all oblique motion is accommodated by trench-parallel strike-slip.

[16] If this discrepancy were due to a northern LA forearc (NLAF), its motion can be constrained by a velocity space diagram in which the slip vectors give the direction of NLAF-NA motion. Because the slip vectors do not give a rate, solving the vector triangle requires assuming a direction of CA-NLAF motion. In many arcs this direction is given by geologic knowledge of the boundary between the sliver and overriding plate. Here, given the absence of direct evidence for such a boundary, we assume that it is parallel to the trench (the boundary between the hypothetical sliver and subducting plate). If so, rough estimates put the sliver moving WNW relative to CA at ~9 mm/yr in the north (Figure 2b) and ~4 mm/yr to the south (Figure 2c) resulting in a decreased component of obliquity southward.

[17] The major difficulty proposing the NLAF as a distinct entity, and if so, whether it is a block or if it deforms internally, is the absence of geologic evidence for boundaries of the presumed NLAF block and of geodetic data within the block directly showing its motion. The fact that GPS data from FSD0/1, BARB and TDAD are consistent with the overall motion of CA suggest the possible NLAF's west boundary lies east of Martinique and does not extend south of 14°N. However, these data are indirect, in that they show only what is not part of the presumed block. Given that we do not have GPS data within the NLAF, even if it moves distinctly from both CA and NA, it need not move as a rigid block, as we have assumed for simplicity. Our data would also be consistent with the NLAF deforming internally as proposed by *Feuillet et al.* [2002] based on the observations of normal faults in the vicinity of Guadeloupe that strike SW and NE, representing arc-parallel extension with LA's northern portion moving in a similar manner to what we propose here. Only two strike-slip mechanisms northwest of the island (Figure 2) are available to relate them to the mapped NW-striking faults in that location and may represent the NLAF's western boundary. Similarly, another event east of Martinique has the same mechanism, suggesting the sliver's western boundary. How-

ever, these events may equally reflect right-lateral bookshelf faulting.

[18] Curiously, the hypothetical NLAF block roughly coincides with the northern portion of the arc, which has many more earthquakes than the less seismically active southern half. No compelling explanation has been offered for this difference. Suggestions include a change across the NA-SA boundary (though it is unclear why the expected small difference in motion should matter) [*Vierbuchen*, 1979], thicker sediments from the Orinoco river [*Wright*, 1981] lubricating the plate interface, and a seismic gap. Whether this is a gap where future large events are expected is unclear. The fact that motions of BARB and FSD0/1 are consistent with those of the CA plate indicate that they are not perturbed by the effects of elastic strain accumulation due to the seismic cycle. This would be consistent with the earthquake history implying that much of the plate convergence occurs aseismically [*Stein et al.*, 1986], though some large thrust events may still occur [*Bernard and Lambert*, 1988].

[19] In summary, the long-recognized discrepancy between the slip vectors of thrust fault earthquakes at the LAT and the predicted direction of NA-CA convergence persists with better estimates of the plate motion and a larger slip vector data set. The discrepancy suggests that a NLAF block moves distinctly from both major plates. Confirming this hypothesis would require GPS data from within the block and geologic data for its boundaries.

[20] **Acknowledgment.** We thank J. DeChabalier, J. Ruegg and the IPGP for Martinique GPS data, and R. Bürgmann and an anonymous reviewer for useful comments.

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