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Strain partitioning and fault slip rates in the northeastern Caribbean from GPS measurements

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[1] GPS data collected in the Dominican Republic from 1994 to 2001 show that oblique convergence between the North American and Caribbean plates is partitioned between 5.2 ± 2 mm.yr⁻¹ of dip-slip reverse motion on the North Hispaniola thrust (approximately N-S), and 12.8 ± 2.5 mm.yr⁻¹ and 9.0 ± 9.0 mm.yr⁻¹ of approximately E-W left-lateral strike-slip motion on the Septentrional and Enriquillo faults (95% confidence). The agreement between GPS and paleoseismological slip rates on the Septentrional fault, together with the 770–960 years since the last major earthquake and the 800–1200 years maximum repeat time of major earthquakes, may indicate that the Septentrional fault is currently in the late phase of its rupture cycle. *INDEX*

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1. Introduction

[2] The boundary between the Caribbean and North American plates in the northeastern Caribbean offers an excellent example of transition from strike-slip to oblique subduction [Figure 1; Calais *et al.*, 1992; Mann *et al.*, 1998]. However, strain distribution across and along the plate boundary zone as well as slip rates on the major active faults remain to be determined over most of the plate boundary zone. Understanding strain distribution and slip rates are important for two reasons. First, these data will allow us to test and improve models of plate interaction within the context of oblique subduction. Second, it will provide much needed data to assess seismic hazard in a region that experienced several large earthquakes in the 16th through 19th centuries and has among the highest popula-

tion densities in the world (16.5 million total) concentrated on a seismogenic plate boundary.

2. GPS Data and Results

[3] We analyzed the GPS data from a 35 site network covering the Dominican Republic using the GAMIT software, including 10 global IGS stations to serve as ties with the ITRF2000. We combined our regional daily solutions with global SINEX (Solution Independent Exchange format) files from the IGS daily processing routinely done at Scripps Institution of Oceanography and imposed the reference frame by minimizing the position and velocity deviations of IGS core stations with respect to the ITRF2000 while estimating an orientation, translation and scale transformation. We finally rotated our ITRF2000 velocities in a North American plate frame by removing the rigid rotation of the North American plate as defined by *DeMets et al.* [2000] (Table 1, Figure 1). We find long term baseline repeatabilities on the order of 2–4 mm for the horizontal components and 5 to 10 mm for the vertical component. We find horizontal velocity uncertainties on the order of 2–3 mm.yr⁻¹ (1- σ), allowing daily stochastic variations of site coordinates of 0.5 mm²/day in order to account for a noise model combining white and flicker noise.

[4] The results from the 1994–2001 GPS observations (Figure 1) show a NS gradient in the GPS-derived velocities across Hispaniola, suggesting elastic strain accumulation on locked faults. At least four major active faults in the Hispaniola area have been clearly identified from onland and offshore mapping: (1) The North Hispaniola fault, a low angle thrust that follows the northern margin of the island [Dillon *et al.*, 1994; Dolan *et al.*, 1998], responsible for a series of M7.2–8.1 thrust earthquakes in 1943–1953 [Dolan and Wald, 1998], and continuous with the Puerto Rico trench to the east; (2) The left-lateral Septentrional fault, responsible for the late Neogene uplift of the Cordillera Septentrional and for active folding and faulting at its contact with late Neogene to Holocene units of the Cibao valley [Mann *et al.*, 1998; Prentice *et al.*, in press]; (3) The east-west-striking Enriquillo fault, that follows the southern peninsula of Haiti into the Enriquillo valley in the Domi-

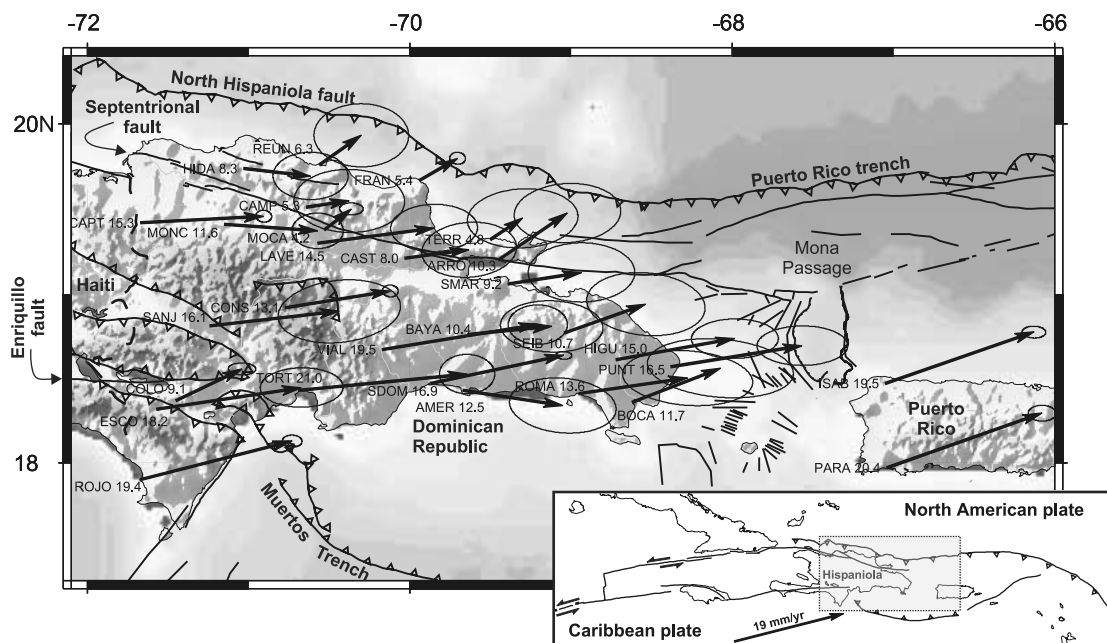


Figure 1. GPS-derived velocities in the Dominican Republic and western Puerto Rico with respect to the North American Plate. The arrow length is proportional to the displacement rate, indicated in mm.yr^{-1} next to the site code name. The ellipses represent 95% confidence intervals. Most sites in the Dominican Republic have only been observed twice two years apart in 1999 and 2001. Note the more northerly vectors along the north coast, reflecting northward thrusting of the Septentrional sliver at the North Hispaniola fault zone. Bottom inset shows the study area.

nican Republic [Mann *et al.*, 1995], and may connect further east with the Muertos trough; (4) The low angle Muertos thrust, apparently active in its westernmost part, but showing decreasing activity eastwards with little or no active underthrusting east of 65W [Masson and Scanlon, 1991]. Other faults, in particular the Guacara-Bonao and San Juan-Los Pozos faults, have evidence of late Cenozoic motion, but with no present-day displacement yet reported. We assume that these faults are either non-active or slipping at very slow rates (less than the resolution of the GPS measurements) and therefore do not consider them in the rest of the analysis.

3. Elastic Strain Accumulation Models

[5] We use prior information on active structures in the northeastern Caribbean to construct a simple deformation model in an homogeneous elastic half-space, assuming strain accumulation on four active faults, locked to a depth of 15 km and freely slipping below that depth [e.g., Savage, 1983]. Fault location, dip, strike, and sense of slip are constrained by geologic investigations. Most hypocenters of shallow earthquakes (<30 km) in the northeastern Caribbean are located near 15 km [Calais *et al.*, 1992; Deng and Sykes, 1995; Dolan *et al.*, 1998], consistent with a continental or transitional crust of normal heat flow.

[6] Dixon *et al.* [1998] used GPS data at 4 sites in the Dominican Republic to model elastic strain accumulation in two dimensions on three parallel and vertical strike-slip faults. In this study, we use the 30-site GPS data set shown on Figure 1 to model elastic strain in three-dimensions, including the plate boundary-perpendicular component. We explicitly account for the low-angle nature of the North

Hispaniola-Puerto Rico and Muertos faults, as well as the three dimensional geometry of the fault pattern. Our model contains 6 adjustable parameters (strike-slip and dip-slip components on the North Hispaniola and Muertos faults, strike-slip component only on the Septentrional and Enriquillo faults) and 30 GPS velocities. We explore the parameter space with grid searches, scoring each model by its reduced chi-square statistic defined by $\chi_r^2 = [\sum_{i=1}^N (O_i - C_i)^2 / \sigma_i^2] / (N-P)$, where N is the number of data, P the number of adjustable parameters, O_i the observed GPS velocity with its associated uncertainty σ_i , and C_i the velocity from an elastic strain accumulation model. We also compute the associated probability for a 95% confidence level.

[7] Since strike-slip motion is predominant along the northern Caribbean plate boundary in Hispaniola, there is a trade-off in the models between the amount of strike-slip motion on the Enriquillo, Septentrional, and North Hispaniola faults. In addition, the North Hispaniola fault may combine strike-slip and thrust motion, as suggested by earthquake focal mechanisms [Dolan and Wald, 1998]. In contrast, there is no evidence of significant present-day reverse motion on the Enriquillo and Septentrional faults from seismological and paleoseismological data. We there-

Table 1. Best-Fit Fault Parameters

Fault	dip (deg.)	Lock. depth (km)	strike-slip (mm.yr^{-1})	dip-slip (mm.yr^{-1})
SF	90	15	12.8	0
EF	90	15	9.0	0
NHF	30	15	0	5.2
MT	-20	15	0	0

SF = Septentrional fault, EF = Enriquillo fault, NHF = North Hispaniola fault, MT = Muertos trough.

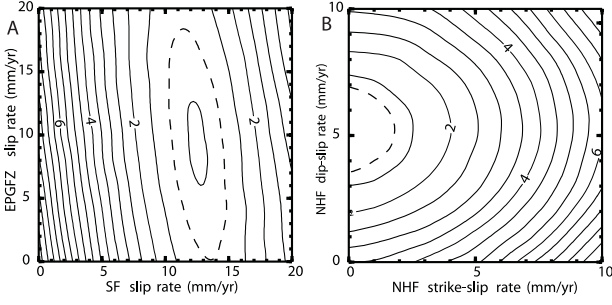


Figure 2. Contour plots of the χ_r^2 statistic. The dashed line show the limit of the 95% confidence area. (a) χ_r^2 statistic for the [Enriquillo strike-slip, Septentrional strike-slip] tests. (b) χ_r^2 statistic for the [North Hispaniola strike-slip, North Hispaniola dip-slip] tests.

fore searched the parameter space by combining a grid search in the [North Hispaniola strike-slip, North Hispaniola dip-slip] domain with a grid search in the [Enriquillo strike-slip, Septentrional strike-slip] domain. We set up a [North Hispaniola strike-slip, North Hispaniola dip-slip] grid with slip rate for both components varying from 0 to 10 mm.yr^{-1} . At each grid point, we compute a series of [Enriquillo strike-slip, Septentrional strike-slip] models, with slip rates varying from 0 to 20 mm.yr^{-1} , and find the one that provides the lowest χ_r^2 . We obtain an overall minimum χ_r^2 with 5.2 mm.yr^{-1} of dip-slip (reverse) motion and 0 mm.yr^{-1} strike-slip motion on the North Hispaniola fault. We repeated the same procedure, varying the dip-slip rate on the Muertos fault from 0 to 10 mm.yr^{-1} and found that the lowest overall χ_r^2 was obtained with 0 mm.yr^{-1} of slip on the Muertos fault.

[8] We then used the slip rates found above for the North Hispaniola and Muertos trough and ran a series of models in the [Enriquillo strike-slip, Septentrional strike-slip] domain with slip rates on the Enriquillo and Septentrional faults varying from 0 to 20 mm.yr^{-1} . Figure 2a show that a minimum χ_r^2 is obtained for 12.8 mm.yr^{-1} and 9.0 mm.yr^{-1} of left-lateral slip on the Septentrional and Enriquillo faults, respectively. The associated uncertainties, at the 95% confidence level, are 2.5 mm.yr^{-1} and 9.0 mm.yr^{-1} , respectively. The large uncertainty on the Enriquillo slip rate reflects the fact that we have no GPS sites or observations along the 250 km-long trace of the Enriquillo fault on the southern peninsula of Haiti (Figure 1). Similarly, fixing the Enriquillo and Septentrional slip rates to 12.8 mm.yr^{-1} and 9.0 mm.yr^{-1} , respectively, leads to uncertainties of 1.7 mm.yr^{-1} and 1.8 mm.yr^{-1} for the dip-slip and strike-slip component on the North Hispaniola fault, respectively (Figure 2b). Finally, the overall rms of our best-fit model (Table 2) is 2.6 mm.yr^{-1} , consistent with the GPS velocity uncertainties.

4. Discussion

[9] The above analysis of the GPS velocities in terms of elastic strain accumulation shows that the data favor a model in which oblique Caribbean-North America plate motion in the Hispaniola area is totally partitioned between left-lateral shear on the Enriquillo and Septentrional faults, and thrust on

the North Hispaniola fault. This result is consistent with marine geophysical studies offshore northern Hispaniola, that show a small accretionary prism at the toe of the continental margin, with active folds and north-verging reverse faults, consistent with pure north-south shortening [Dillon *et al.*, 1992; Dolan *et al.*, 1998]. The model also agrees with the focal mechanism proposed by Dolan and Wald [1998] for the largest earthquake to occur in the north-central Caribbean region in the past 400 years (August 4th, 1946, $M_s = 7.8-8.1$). Interestingly, our models do not require slip on the Muertos thrust, although off-shore studies clearly show recent sediments folded and thrust at its western end. Given the current precision of the GPS results and the uncertainties in the elastic strain accumulation models (fault geometry, locking depth, crustal rheology), we believe that we cannot resolve slip rates less than 3 mm.yr^{-1} .

[10] The Quaternary trace of the Septentrional fault has been mapped over most of its 320 km-long subaerial extent and its offshore extensions near Haiti and Puerto Rico [Mann *et al.*, 1998; Dolan *et al.*, 1998; Grindlay *et al.*, 2000]. Offset stream terrace risers at two localities provide fault slip data that, coupled with radiocarbon ages, indicate a Holocene strike-slip rate of 6–12 mm.yr^{-1} [Prentice *et al.*, in press]. The $12.8 \pm 2.5 \text{ mm.yr}^{-1}$ slip rate on the Septentrional fault derived from the GPS data is consistent with these results within their uncertainties.

[11] In addition, exposures of the fault zone in excavations at several sites to the west of the offset river terraces show that the most recent ground-rupturing earthquake occurred between AD 1040 and AD 1230 and involved a minimum of 4 m of left-lateral slip [Prentice *et al.*, in press].

Table 2. Velocities (V , mm.yr^{-1}) With Respect to the North American Plate and Associated One Standard Deviation Formal Errors (σ , mm.yr^{-1})

Site	lon	lat	V_e	V_n	σ_e	σ_n	Corr.
AMER	-69.7	18.4	12.4	-1.9	2.7	1.4	-0.129
ARRO	-69.5	19.2	8.6	5.8	2.7	1.5	0.067
BAYA	-69.6	18.8	10.4	1.0	2.6	1.3	-0.053
BOCA	-68.6	18.4	10.9	4.2	3.7	1.5	-0.179
CAMP	-70.6	19.5	5.3	0.8	2.8	1.6	-0.016
CAPT	-71.7	19.4	15.3	0.8	0.4	0.3	-0.066
CAST	-70.0	19.2	8.0	1.1	2.4	1.4	0.095
COLO	-71.5	18.4	8.2	3.9	0.7	0.3	-0.041
CONS	-70.8	18.9	13.0	2.0	0.4	0.3	-0.044
ESCO	-71.6	18.3	18.0	2.7	2.1	1.0	0.020
FRAN	-69.9	19.7	4.7	2.7	0.4	0.3	-0.049
HIDA	-71.0	19.7	8.3	-0.9	1.9	1.2	-0.004
HIGU	-68.7	18.6	14.7	2.6	2.2	1.0	0.011
ISAB	-67.0	18.5	18.4	6.4	0.6	0.3	-0.037
LAVE	-70.6	19.3	14.4	1.9	2.2	1.2	0.016
MOC	-70.5	19.4	3.3	2.6	0.6	0.3	-0.030
MONC	-71.2	19.4	11.6	-0.8	1.3	0.9	-0.004
PARA	-67.0	18.0	19.2	6.8	0.7	0.4	-0.017
PUNT	-68.4	18.6	16.3	2.6	2.3	1.0	0.005
REUN	-70.6	19.8	5.2	3.7	2.4	1.6	-0.004
ROJO	-71.7	17.9	18.8	4.8	0.5	0.3	-0.054
ROMA	-69.0	18.4	13.4	1.9	3.3	1.4	-0.152
SANJ	-71.2	18.8	16.0	1.8	3.1	1.6	0.160
SDOM	-69.9	18.5	16.5	3.5	0.4	0.2	-0.060
SEIB	-69.0	18.8	10.1	3.6	3.0	1.6	-0.123
SMAR	-69.4	19.1	9.1	1.4	2.7	1.5	0.004
TERR	-69.5	19.3	4.0	2.6	2.8	1.5	0.069
TORT	-70.7	18.4	20.9	2.0	1.4	1.0	-0.009
VIAL	-70.2	18.7	19.3	3.1	1.5	1.0	-0.000

In trenches, the lack of deformation on horizons younger than this event suggests that the central segment of the Septentrional fault zone has not ruptured during a major earthquake in the past 770–960 years. In addition, *Prentice et al.* [in press] show that the penultimate event on the Septentrional fault occurred post AD 30, suggesting a maximum recurrence interval of 800–1200 years. It has been shown that geodetic rates near an active fault approach geologic rates in the late part of the seismic cycle. Early in the seismic cycle, viscoelastic relaxation effects result in geodetic rates faster than the geologic ones, at least for low relaxation time/earthquake repeat time ratios [e.g., *Savage and Lisowski*, 1998]. Consequently, the 770–960 years since the last major ground-rupturing earthquake and the 800–1200 years maximum repeat time of major earthquakes, together with the agreement between GPS and paleoseismological slip rates on the Septentrional fault found here, may indicate that the Septentrional fault is currently in the late phase of its rupture cycle.

[12] A fully locked fault accumulating elastic strain at $12.8 \pm 2.5 \text{ mm.yr}^{-1}$ implies a current slip deficit of between 7.9 and 14.7 m since the last major earthquake. This could correspond to a $M_w = 7.7$ to 7.9 earthquake if this slip deficit was entirely released today in a single event [*Wells and Coppersmith*, 1994]. The geometry of the Septentrional fault, a single and essentially continuous active fault trace for at least 250 km [*Mann et al.*, 1998], makes it capable of accommodating such a large earthquake. The Septentrional fault is, therefore, a source of high seismic potential in a densely populated area of vital economical importance for the Dominican Republic.

5. Conclusions

[13] The analysis of the GPS data collected in the Dominican Republic from 1994 to 2001 show that the oblique convergence between the North American and Caribbean plates is partitioned between $5.2 \pm 2 \text{ mm.yr}^{-1}$ of dip-slip reverse motion on the North Hispaniola thrust, and $12.8 \pm 2.5 \text{ mm.yr}^{-1}$ and $9.0 \pm 9.0 \text{ mm.yr}^{-1}$ of left-lateral slip on the Enriquillo and Septentrional faults, respectively. Integrated with paleoseismology data, these results indicate that seismic hazard is currently high on the Septentrional fault. However, other less well known faults such as the Enriquillo fault in southern Hispaniola, running which runs a few kilometers south of the Haitian capital of Port-au-Prince, may also be potential sources of significant earthquakes and merit additional studies.

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