Character of the Caribbean–Gônave–North America plate boundaries in the upper mantle based on shear-wave splitting

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Received 5 September 2012; revised 5 November 2012; accepted 8 November 2012; published 19 December 2012.

[1] We present new shear-wave splitting measurements of SKS, SKKS, PKS, and sSKS phases from eight stations in the northern Caribbean. Prior to this work, shear-wave splitting analysis of the northern Caribbean boundary was only evaluated at a station in Puerto Rico. Stations that lie within several tens of kilometers of microplate boundaries have mean fast polarization directions parallel to the boundary and have delay times greater than 1 s. Stations more than several tens of kilometers away from microplate boundaries show no evidence for an anisotropic upper mantle. Stations in Cuba and Jamaica have fast axes oriented ~100° with delay times of ~1.5 s, indicating that the east-striking left-lateral strike-slip faults that define the north and south boundaries of the Gônave microplate continue into the upper mantle. A station located in Antigua, where the North America plate subducts beneath the Caribbean plate, has a high degree of splitting with the fast axis parallel to the trench. Based on our results, the deformation related to the presence of microplates in the northern Caribbean extends into the upper mantle.
Citation: Benford, B., B. Tikoff, and C. DeMets (2012), Character of the Caribbean–Gônave–North America plate boundaries in the upper mantle based on shear-wave splitting, *Geophys. Res. Lett.*, *39*, L24303, doi:10.1029/2012GL053766.

1. Introduction

[2] Seismic anisotropy is a powerful tool for understanding mantle deformation since it is based mainly on the preferred orientation of minerals, primarily olivine, in response to tectonic strain [e.g., *Mainprice et al.*, 2000]. The upper mantle is composed primarily of olivine (70%) and deformation of this mineral produces a lattice-preferred orientation, which imparts an anisotropy [*Crosson and Lin*, 1971]. In an anisotropic upper mantle, shear waves split into fast and slow components and are transversely polarized [*Savage*, 1999]. Seismic anisotropy analysis enables the determination of the polarization direction (ϕ) of the fast shear wave and the delay time (∂t) between the arrival of the fast and slow waves, where ϕ and ∂t are the result of the foliation and lineation in the upper mantle and ∂t is the result of both the degree of anisotropy and the thickness of the layer [e.g., *Silver and Chan*, 1991]. For the shear waves considered here, between the depths of 100 and 200 km, Fresnel zones have radii between 40 and 60 km [e.g., *Alsina and Snieder*, 1995], which allows for lateral variations in the degree of fabric development to be observed.

[3] To understand the structure of the upper mantle, shear waves are ideal because the observed anisotropy can be constrained to the receiver side, the propagation direction of each wave is nearly constant [*Silver and Chan*, 1991], and any transverse energy at the receiver is a result of anisotropy since the S-wave is radially polarized at the core-mantle interface [*Silver and Chan*, 1991].

[4] Active deformation in the northern Caribbean is already well studied. Obliquely convergent left-lateral slip of 19–20 mm yr^{-1} between the Caribbean and North America plates [*DeMets et al.*, 2010] (Figure 1), appears to drive westward movement of the Puerto Rico-Virgin Islands (PRVI), Hispaniola, and Gônave microplates [*Mann et al.*, 1995; *Benford et al.*, 2012a]. GPS measurements show 2.6 $\pm$ 2.0 mm yr^{-1} of westward motion of the PRVI microplate relative to the Caribbean plate [*Jansma and Mattioli*, 2005] and 7–13 mm yr^{-1} of westward Gônave microplate motion [*DeMets and Wiggins-Grandison*, 2007; *Benford et al.*, 2012b], consistent with extension between Puerto Rico and Hispaniola [*Jansma and Mattioli*, 2005]. In a related paper, we modeled a 126-station GPS velocity field for the Caribbean plate and its northern boundary to better understand the geometry of present deformation, fault slip rates, and presence of microplates [*Benford et al.*, 2012a]. Here, using shear-wave splitting, we provide data about upper mantle anisotropy at the northern Caribbean boundary and show that the deformation associated with the presence of microplates extends into the upper mantle.

2. Data and Methods

[5] We analyzed seismograms from eight broadband stations on the islands of Jamaica, Hispaniola, Cuba, Puerto Rico, Grand Turk, Barbuda, and St. Thomas (Figure 1). Five stations (ANWB, GRTK, GTBY, MTDJ and SDDR) are from the Caribbean network, SDD is from the Dominican Republic network, SJG is from the IRIS/USGS network, and STVI is from the Puerto Rico network.

[6] We examined events from 2008, 2009, and January of 2010. Station SDD was not operating until the middle of 2009, so we extended its window to August of 2011. Station SJG in Puerto Rico is part of the previous studies of *Russo et al.* [1996] and *Piñero-Feliciangeli and Kendall* [2008].

[7] Our analysis includes events that are 85°–140° from the broadband station and have a minimum moment magnitude (M_w) of 5.5, the minimum required for a necessary signal-to-noise ratio of 5:1. For each station, we obtained between 225 and 650 events that fit these criteria. Many events did not show a clear arrival of the particular phase on the transverse or rotational component and were discarded. The National Earthquake Information Center preliminary

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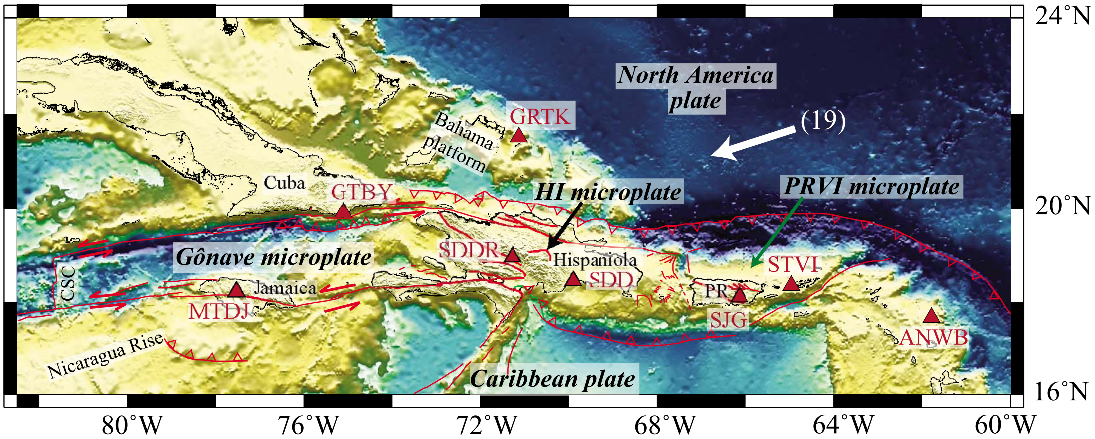

Figure 1. Tectonic setting of the northern Caribbean. Bold white arrow - MORVEL estimate of North America plate motion in mm yr^{-1} relative to the Caribbean plate [*DeMets et al.*, 2010]. Abbreviations: CSC - Cayman spreading center, HI - Hispaniola, PRVI - Puerto Rico-Virgin Islands, and PR - Puerto Rico. 2-min seafloor bathymetry and land topography from *Sandwell and Smith* [1997].

determination of epicenters catalog (U.S. Geological Survey) was used for event locations and origin times.

[8] Inversion of the data to determine ϕ and ∂t was done using the Matlab-based program *SplitLab* [*Wüstefeld et al.*, 2008], which uses three methods simultaneously to determine the shear-wave splitting parameters ∂t and ϕ (Figure S1 in the auxiliary material), namely, the rotation correlation method [*Bowman and Ando*, 1987], the minimum eigenvalue method [*Silver and Chan*, 1991], and the minimizing transverse component method [*Silver and Chan*, 1991].[1] *SplitLab* also assigns a quality level to each event. Here, we present events where there is good agreement between the results of the three methods.

[9] We carried out 412 splitting measurements. Of these, 246 were non-null measurements (a definite splitting of the shear wave is observed); the remaining measurements are null (the shear wave has not been split). In Data Sets S1 and S2 of the auxiliary material, we present the following results for each event: the phase used, the backazimuth and angle of incidence of the event, the manually applied filter, the determined splitting parameters and the uncertainties determined from the 95% confidence interval for the three methodologies. Each event is also assigned a quality of good, fair, poor, fair null, or good null. Figure S1 gives an example of an event with good-quality splitting. The rating is based on: 1) a high signal-to-noise ratio, 2) a small confidence region, 3) good linearization of the transverse component, 4) good correlation between the two split shear waves, and 5) good correlation between the rotation-correlation and minimum energy methods. Ratings of good, fair, or poor meet all five, four, or three or fewer of these criteria, respectively. Filtering was applied manually in order to maximize the signal-to-noise ratio. Most events were bandpass filtered using a combination of corner frequencies typically between 0.01 and 0.2 Hz.

[10] We determined 166 null measurements (Data Set S2 in the auxiliary material). *Bonnin et al.* [2010] suggest three reasons for null measurements: 1) The incoming wave only traveled through an isotropic medium, 2) The polarization of the incoming wave is parallel to the slow or fast direction in the anisotropic medium, or 3) Two anisotropic layers with orthogonal fabrics cancel out each other's delay time. Additionally, *Vauchez et al.* [2005] suggest null measurements may be the result of a subhorizontal foliation and a dominant fibre-[010] fabric in the mantle, which results in a low intrinsic value and the minimum anisotropy is normal to the foliation. Null events that have a "good" quality are events with a high signal-to-noise ratio on the radial component and minimal energy on the transverse component. Fair nulls are events that have minimal energy on the transverse component but not enough to observe splitting.

3. Results

[11] In evaluating splitting at each station, we consider both fair and good non-null measurements (Figures 2 and 3, Table 1, and Data Sets S1 and S2). Below we present the mean ∂t and ϕ with 1-σ uncertainties using the rotation correlation method. We prefer this method because the eigenvalue method consistently determined high (>3 s) ∂t and the transverse component method has high uncertainties associated with its solutions (Data Set S1).

[12] We first compare our results for station SJG in Puerto Rico with those of the *Russo et al.* [1996] and *Piñero-Feliciangeli and Kendall* [2008] studies, including events from the time window of *Russo et al.* and from January 2008 to December 2009. Based on nine measurements, *Russo et al.* [1996] and *Piñero-Feliciangeli and Kendall* [2008] determined ϕ was oriented 85° ± 1° and ∂t = 1.2 ± 0.2 s and 90.7° ± 9.0° and 1.29 ± 0.27 s, respectively. For our analysis and using 10 measurements, we determined that ϕ is oriented 101° ± 20° with ∂t = 1.2 ± 1.1 s (Table 1). Our results agree within the uncertainties of both studies, however, our uncertainties are significantly larger. Based on the number of measurements, our larger uncertainties are consistent with other Splitlab analyses [e.g., *Barruol et al.*, 2011]. Additionally, if we calculate the mean and its uncertainty from the *Russo et al.* [1996] results, using the method employed in this study, it increases the uncertainty

[1] Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2012gl053766. Other auxiliary material files are in the HTML. doi:10.1029/2012GL053766.

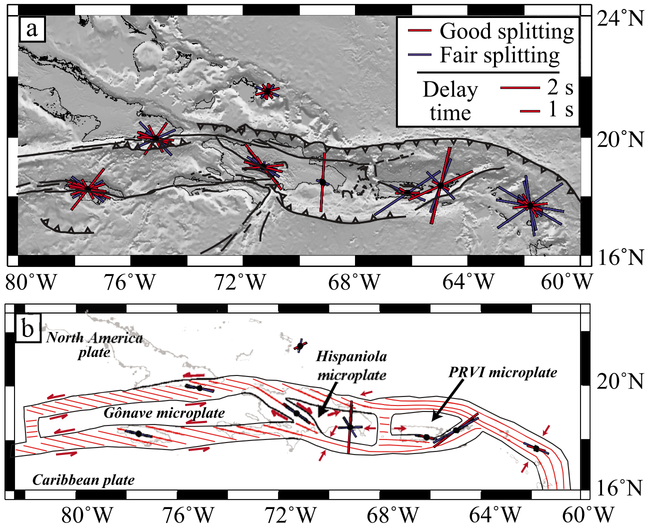

Figure 2. (a) Each individual good (red) or fair (blue) splitting result with fault traces (black). (b) Means of the good (red) and of the fair and good combined (blue) splitting results. Interpreted upper mantle fabric (shown in red) based on fast-axis orientations with a vertical foliation and horizontal lineation. Arrows show plate motion at boundaries. The line azimuth indicates the trend of ϕ and line length is proportional to the magnitude of ∂t.

in ϕ and ∂t by ~3 times. For this reason, we prefer to use the rose diagrams (Figure 3) rather than the calculated mean.

[13] No fair or good non-null or null measurements were recorded at station PUCM (70.68°W, 19.44°N, not shown in figures) in northern Hispaniola suggesting that the data are poor at this locality. We were able to measure three splitting events at station SDD in Puerto Rico indicating that either the time span was not long enough or that a strong fabric is not present beneath this station. Station STVI in the U.S. Virgin Islands (Figure 1) records unusually high ∂t and has a high uncertainty and a high degree of scatter in ϕ, making determination of a fabric beneath this station not yet possible.

[14] The highest ∂t and lower uncertainties in ϕ occur at stations located near active plate boundaries (Figures 1 and 3): station MTDJ in Jamaica and GTBY in Cuba. MTDJ is located on the east-west left-lateral Gônave-Caribbean plate boundary, where slip rates are estimated at 6.5 ± 0.5 mm yr^{-1} [*Benford et al.*, 2012b]. GTBY occurs on the east-west left-lateral Gônave-North America plate boundary, where slip rates are higher, ~14–15 mm yr^{-1} [*Benford et al.*, 2012a]. Good agreement exists between ϕ and the plate boundary orientation (Figure 3). In contrast, ϕ only agrees with absolute plate motion (Figure 3) when plate motion is subparallel to the plate boundary (e.g., station GTBY). Station GRTK, located in the Bahamas and away from an active plate boundary (Figure 1), has the lowest ∂t and a high degree of scatter in ϕ (Figure 3), making it good for comparison with stations located closer to plate boundaries.

4. Discussion

4.1. Gônave Microplate Boundaries

[15] The two stations along the northern and southern left-lateral E-W boundaries of the Gônave microplate have ∂t = ~1.5 s with ϕ oriented subparallel to the boundary (Table 1 and Figures 1–3). In both instances, ϕ is 10–15° clockwise from the left-lateral boundary, consistent with left-lateral shear [e.g., *Ramsay*, 1980] at depth, suggesting that deformation at the north and south boundaries of the Gônave microplate extends into the upper mantle. This result is also consistent with the 5° obliquity in a clockwise-sense measured at the right-lateral Caribbean-South America boundary [*Russo et al.*, 1996]. Finally, although the boundaries move at different rates, the degree of fabric development is comparable.

[16] At station SDDR (Figure 1), ϕ is oriented parallel to the trend of the northwest mountains of central

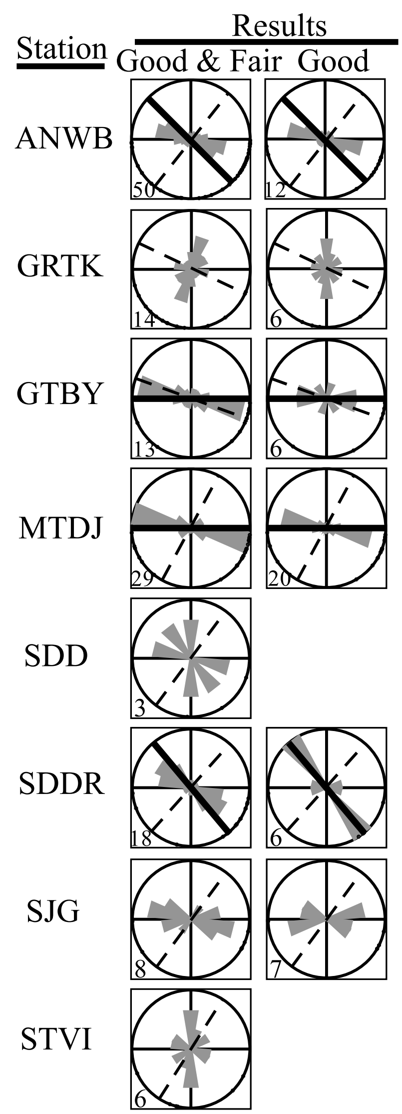

Figure 3. Rose diagrams (left) of good and fair measurements for each station, where the primitive circle equals 52% of the measurements and (right) of good non-nulls, where the primitive equals 67% of the measurements for stations with enough good measurements. For each diagram, the number of measurements (lower left), the trend of absolute plate motion (dashed line; based on the predicted angular velocity at each location relative to ITRF08 from *Benford et al.* [2012a]), and the trend of the nearest plate boundary (solid thick line).

Table 1. Broadband Seismometer Locations and Splitting Results

	Coordinates		Good and Fair Splitting					Good Splitting				
Station Name	Lat. (N)	Long. (W)	φ	σ_φ	∂t	$\sigma_{\partial t}$	Events	φ	σ_φ	∂t	$\sigma_{\partial t}$	Events
ANWB	17.67	61.79	113.5	29.3	1.52	1.04	25	106.0	27.9	1.03	0.42	12
GRTK	21.51	71.13	13.1	44.4	0.83	0.47	14	3.2	48.6	0.76	0.30	6
GTBY	19.93	75.11	104.7	29.4	1.56	0.54	13	99.5	42.3	1.60	0.44	6
MTDJ	18.23	77.53	102.9	24.2	1.50	0.55	29	102.6	24.9	1.52	0.53	20
SDD	18.46	69.92	147.0	37.1	1.35	1.43	3	3.5	–	3.00	–	1
SDDR	18.98	71.29	123.3	27.3	1.37	0.77	18	126.4	25.5	1.82	0.95	6
SJG	18.11	66.15	101.4	20.9	1.23	1.10	10	103.5	15.3	0.85	0.41	7
STVI	18.35	64.96	61.0	54.2	2.89	1.23	6	52.7	49.7	3.13	1.47	4

Hispaniola (Figure 2). Station SDD, located just to the east, has no evidence for a mantle fabric. The anisotropy at SDDR and its orientation may either be a fossil fabric preserved from Cretaceous subduction [*Bowin*, 1966], or a consequence of slow relative motion between distinct Gônave and Hispaniola microplates [e.g., *Benford et al.*, 2012a].

4.2. Caribbean–North America Boundary

[17] At station ANWB, located on Barbuda on the Caribbean plate, just inside the Lesser Antilles subduction zone, ϕ is oriented parallel to the plate boundary. Recent work [*Benford et al.*, 2012a], predicts 10.6 ± 1.5 mm yr^{-1} of left-lateral strike-slip motion and 17.1 ± 1.0 mm yr^{-1} of convergence at the subduction zone front, same as

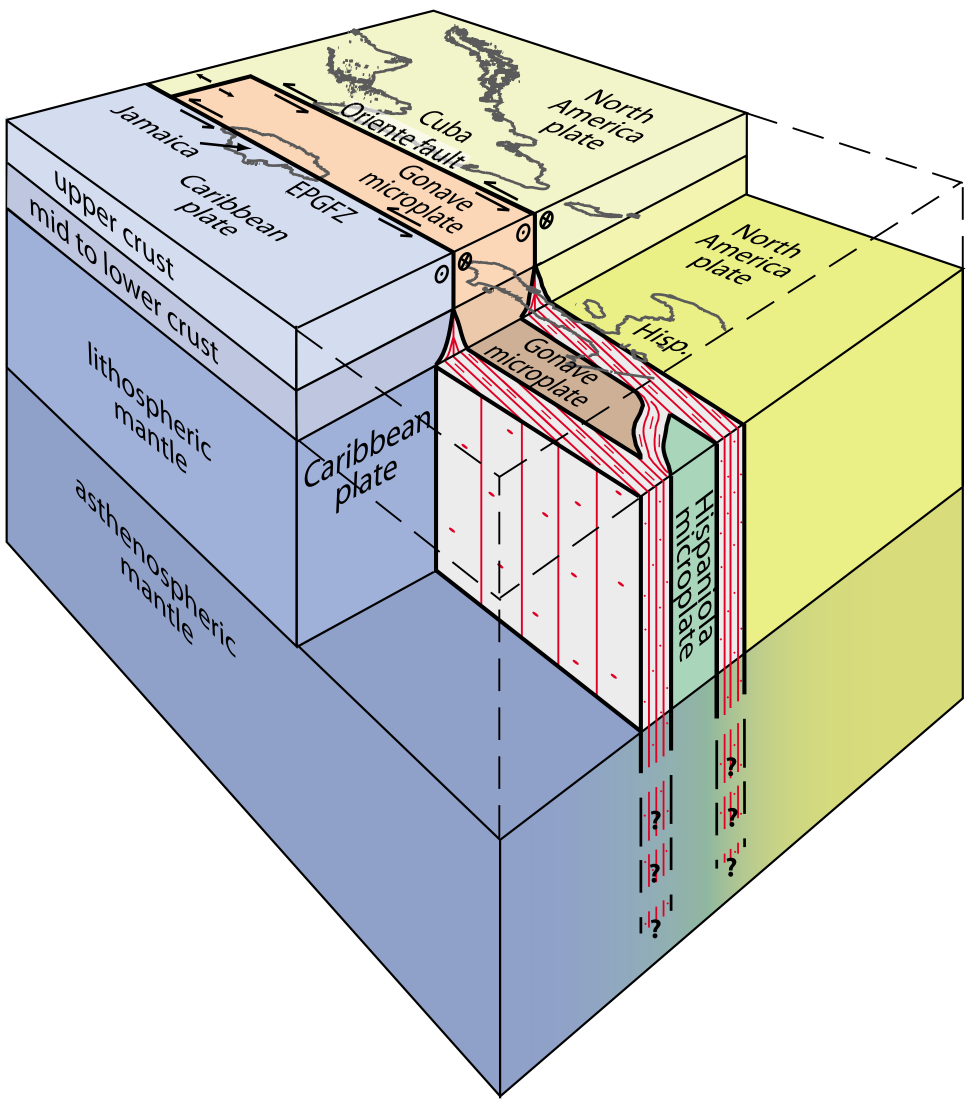

Figure 4. Three-dimensional model for the lithosphere in the northern Caribbean. Fabric (red) has a vertical foliation and horizontal lineation and is localized at borders of microplates, whereas interior of microplates have weak/no fabric.

predicted by the MORVEL Caribbean-North America angular velocity [*DeMets et al.*, 2010]. The observation that ϕ is parallel to the subduction zone is consistent with the large trench-parallel component of plate motion and with the findings of *Piñero-Feliciangeli and Kendall* [2008].

4.3. Character of Microplate Boundaries

[18] The presence of anisotropic fabrics at stations GTBY, MTDJ, and SDDR suggests that deformation associated with the plate boundaries extends into the upper mantle. The weaker/lack of fabric at stations located tens of kilometers from a microplate boundary (GRTK, SDD, SJG, STVI) indicates that upper mantle deformation is localized along the boundaries of the microplate. Of particular relevance is site SDD on Hispaniola, where the absence of anisotropy is consistent with locally undeformed mantle, but where surrounding areas closer to the plate boundary are strongly anisotropic. A similar situation exists with the SJG station on Puerto Rico, which contains only minor anisotropic fabric relative to adjacent sites. One possible interpretation of these results is that microplates of relatively undeformed upper mantle exist below upper-crustal microplates. The inference that crustal deformation continues, although is somewhat wider, in the underlying mantle is consistent with the relatively large delay times observed. That is, the microplates of the northern Caribbean region extend into the mantle.

4.4. Lithospheric-Scale Deformation at Transcurrent Plate Boundaries

[19] Figure 4 shows our interpretation of the three-dimensional lithospheric architecture beneath the northern margin of the Caribbean plate. The obliquity of the fast-wave direction at sites GTBY and MTDJ is consistent with the nearly E-W left-lateral strike-slip along the plate boundaries that define the northern margin of the Caribbean plate. Relative to the deformation on the Caribbean/South American plate boundary [*Russo et al.*, 1996], the SKS delay times are slower, possibly because distributed microplate deformation at the northern boundary of the Caribbean plate decreases the finite strain and hence anisotropic fabric development relative to the fabric expected for a narrower, single-plate boundary.

5. Conclusion

[20] Based on splitting results of shear waves at eight broadband seismometers in the northern Caribbean, we propose that deformation associated with the Caribbean-Gônave, Gônave-North America, and Caribbean-North America plate boundaries continues into the upper mantle. Splitting at the two stations in Cuba and Jamaica is the result of left-lateral strike-slip motion at the northern and southern boundaries of the Gônave microplate. A station in Hispaniola either records a fossil fabric from the Cretaceous or the present-day right-lateral transpressional boundary between the Gônave and Hispaniola microplates. The station located along the northern Lesser Antilles trench records a trench-parallel fast axis. Stations located farther from active plate boundaries do not show evidence for an anisotropic upper mantle.

[21] **Acknowledgments.** We thank Paul Williams and the Earthquake Unit, Neal Lord, and Lee Powell for assistance in data acquisition and processing. We thank Ray Russo for his knowledge of shear-wave splitting and his assistance early on in this project. Support was provided by NSF Tectonics Program grant 0609578.

[22] The Editor thanks Alain Vauchez and an anonymous reviewer for their assistance in evaluating this paper.

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