Evidence for eastward mantle flow beneath the Caribbean plate from neotectonic modeling

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[1] We have applied a thin-shell modeling technique to study the neotectonics of the Caribbean plate. Kinematic conditions computed assuming rotation poles and velocities from NUVEL-1A and from recent geodetic studies have been applied at the lateral boundaries of the model to represent the motion of the adjacent plates with respect to the Caribbean. We have generated a large number of models varying the values of the fault friction coefficient and shear traction on the base of the plate exerted by mantle flow. The quality of the models has been evaluated by comparing their predictions with data on seismic strain rate, stress direction, geodetic baseline changes, and slip rates. Our results indicate that the only successful models are those with low values of fault friction coefficient and significant basal shear traction exerted by eastward mantle flow beneath the Caribbean. *INDEX TERMS:* 3210 Mathematical Geophysics: Modeling; 7218 Seismology: Lithosphere and upper mantle; 8120 Tectonophysics: Dynamics of lithosphere and mantle—general; 8123 Tectonophysics: Dynamics, seismotectonics; 8149 Tectonophysics: Planetary tectonics (5475). **Citation:** Negredo, A. M., I. Jiménez-Munt, and A. Villaseñor (2004), Evidence for eastward mantle flow beneath the Caribbean plate from neotectonic modeling, *Geophys. Res. Lett.*, *31*, L06615, doi:10.1029/2003GL019315.

1. Introduction

[2] It has long been recognized that the Caribbean plate moves generally eastward relative to its two neighboring plates, North and South America. In recent years a growing number of geodetic studies carried out along the margins of the Caribbean basin have provided new, reliable rotation poles between the Caribbean and North America [*DeMets et al.*, 2000] and South America [*Weber et al.*, 2001]. These results can be used to model the neotectonic deformation of the Caribbean region. *Lundgren and Russo* [1996] studied the North America-Caribbean plate boundary zone using an elastic-plate approach. In this study we model the entire Caribbean plate using a more realistic non-linear rheology. Considering the Caribbean plate in its entirety also allows us to investigate the effects of shear traction on the base of the Caribbean lithosphere exerted by sub-asthenospheric mantle flow. *Liu and Bird* [2002] used the same modeling techniques applied here to deduce an overall westward traction (active mantle drag) on the base of the North America plate. However, the deep motion of the subducted Farallon plate, imaged as far east as Florida by tomographic studies, suggests that mantle flow may be relatively eastward under southern North America and Caribbean. East-west directed mantle flow is also inferred from seismic anisotropy studies (SKS splitting) in northeastern Venezuela [*Russo et al.*, 1996].

2. Methodology and Inputs

[3] We have modeled the neotectonics of the Caribbean plate using the thin-shell finite element code SHELLS [*Kong and Bird*, 1995; *Bird*, 1999]. Following the thin-shell approximation, horizontal components of the momentum equation are solved using a 2-D finite element grid. SHELLS predicts long-term-average horizontal velocities, anelastic strain rate, integrated stress and fault slip rates. Our model domain comprises the entire Caribbean plate (Figure 1) and the finite element grid is outlined by fault elements (with double nodes) representing plate boundaries. The grid consists of 1328 triangular continuum elements and 309 fault elements. We have also considered active (or potentially active) intraplate faults, represented on Figure 1. The main plate boundaries and faults (Figure 1) were digitized from the map of *Case and Holcombe* [1980], complemented by new fault maps for Panama [*Cowan*, 1998], Costa Rica [*Montero et al.*, 1998] and Venezuela [*Audemard et al.*, 2000].

[4] Topography and surface heat flow data, together with the assumptions of local isostasy and steady-state thermal regime, were used to determine the crustal and lithospheric mantle thickness. Topography was taken from ETOPO2 data set [*National Geophysical Data Center*, 2001] and we have created a surface heat flow map from data of the new 2°-mean heat flow compilation (G. Masters and G. Laske, A new global heat flow compilation, available at http://mahi.ucsd.edu/Gabi/rem.dir/crust/heatflow.html) complemented by the 5°-mean values from *Pollack et al.* [1993].

[5] Parameters for the crust (predominantly oceanic)/mantle used in these calculations are: reference densities (at 0 K) of 2850/3350 kg m^{-3}, volumetric thermal expansion coefficients of $0/3.5 \times 10^{-5}$ K^{-1}, thermal conductivities of 3.0/3.2 W m^{-1} K^{-1}, constant radioactive heat production of 8×10^{-8} W m^{-3} in the crust (negligible in the mantle). An anelastic nonlinear rheology including frictional-sliding and dislocation-creep flow was assumed (parameters from *Liu and Bird* [2002]).

[6] We obtained different sets of models varying the basal boundary condition and the fault friction coefficient

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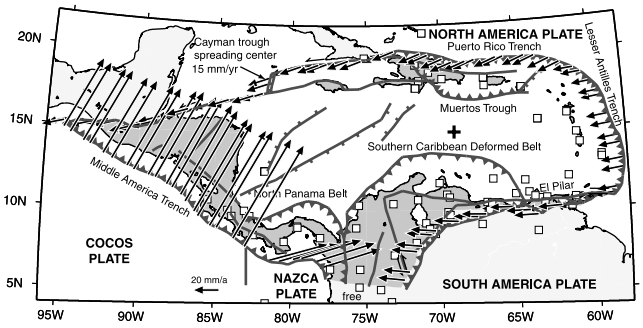

Figure 1. Location map of the Caribbean region. Thick lines are fault systems included in the modeling and the arrows indicate boundary conditions, representing velocities of the adjacent plates with respect to the Caribbean. Open squares show the location of geodetic sites. The thick cross is the location of a model node in the interior of the stable Caribbean plate. See color version of this figure in the HTML.

(between 0.03 and 0.30). Velocity conditions at plate boundaries were applied to nodes lying in the neighbouring plates and they represent motion of these plates with respect to the Caribbean (Figure 1). We used the Euler pole and rotation velocities of Nazca and Cocos with respect to Caribbean from the global plate model NUVEL-1A [*DeMets et al.*, 1994], and velocities predicted by the geodetic studies of *Weber et al.* [2001] for the Caribbean-South American relative motion and *DeMets et al.* [2000] for the Caribbean-North America. Moreover, taking into account studies which propose a E-W direction of mantle flow beneath the Caribbean plate [*Russo and Silver*, 1994; *Russo et al.*, 1996], we have evaluated a basal boundary condition assuming that the sub-asthenospheric mantle moves as a rigid plate in the E-W direction with respect to Africa, which is considered as fixed. We have varied the sub-asthenospheric mantle velocity between −10 to 30 mm/yr (positive values indicate eastward direction). This condition is applied at 400 km depth, and the magnitude of shear traction transmitted to the base of the plate is controlled by the rheologic parameters and by the temperature of the asthenosphere (1150 C).

3. Model Validation

[7] To evaluate the quality of the modeling results we compare the model predictions with five datasets: seafloor spreading rates, fault-slip rates, horizontal velocities from geodetic studies, seismic strain rate distribution and maximum compressive horizontal stress directions. As our reference frame is the Caribbean plate, an additional constraint is that the velocity of the stable interior of the plate must be close to zero. We therefore consider the velocity predicted for a central point in the plate (Figure 1) as a measure of the velocity error. The only spreading center in the Caribbean is the Cayman Trough, with a spreading rate of 15 mm/yr [*Rosencrantz et al.*, 1988]. Values of fault slip rates have been taken from the compilation of *Mann and Burke* [1984] updated with more recent fault maps in the region [*Cowan*, 1998; *Montero et al.*, 1998; *Audemard et al.*, 2000].

[8] Model-predicted horizontal velocities have been compared with 78 geodetic data in the Caribbean plate, mainly distributed along the plate boundaries (6 data from *Dixon et al.* [1998], 21 from *Pérez et al.* [2001], 3 from *MacMillan and Ma* [1999], 8 from *Weber et al.* [2001], 22 from *Trenkamp et al.* [2002], 4 from *DeMets et al.* [2000] and 14 from *Mann et al.* [2002]; see location in Figure 1). In order to avoid the problem of using different reference frames, the comparison is carried out with the difference of projected velocity between each pair of sites (of the same geodetic study) along its baseline. This baseline change is a measure of the shortening or extension between each pair of sites. In order to have a single value of geodetic misfit, we calculated the weighted average error of the baseline changes, with weights depending on the uncertainty of geodetic data.

[9] To calculate the seismic strain rate we used a newly assembled earthquake catalog for the 20th century [*Engdahl and Villaseñor*, 2002]. Magnitudes from different sources and scales were reduced to surface wave magnitude (M_S). We calculated the seismic strain rate and the correlation with model-predicted strain rate using the procedure described by *Jiménez-Munt et al.* [2001]. Our sources for maximum compressive horizontal stress directions are the World Stress Map database (available online at www.world-stress-map.org) and the focal mechanisms of the area compiled in the Harvard CMT catalog [*Dziewonski et al.*, 1981] for the period 1977–2002.

4. Results and Discussion

[10] Figure 2 shows the misfit between each numerical model and the six datasets used. Figures 2a–2d show the errors for different types of kinematic data (seafloor spreading, fault slip rates, velocity of plate interior and geodetic velocities). All plots follow the same pattern, characterized by a clear reduction of errors when applying an eastward (positive) basal velocity condition. In contrast, when no basal shear traction is allowed, the imposed westward motion of North and South America with respect to the Caribbean is almost entirely transmitted to the Caribbean, which moves westward with almost complete coupling to the Americas, even for very low fault friction coefficients. This model grossly violates the observed relative plate motions, and also predicts low values of the Cayman spreading rate (Figure 2a); low values of slip rates along the North and South America boundaries (Figure 2b); high values of the plate interior velocity (Figure 2c); and high errors of baseline changes (Figure 2d). This unrealistic distribution of deformation is also reflected in a low coefficient of correlation with the seismic strain rate (Figure 2e). Results are significantly improved when the tendency for westward drift of the Caribbean plate is counteracted by basal shear traction exerted by imposed basal eastward mantle flow. This suitable decoupling of the Caribbean with respect to North and South America is also favored by low fault friction coefficients. The correlation with the seismic strain rate favors models with low fault friction coefficient (Figure 2e), where the strain is more distributed along faults on the plate boundary, in good agreement with earthquakes location (Figure 3). In contrast, stress direc-

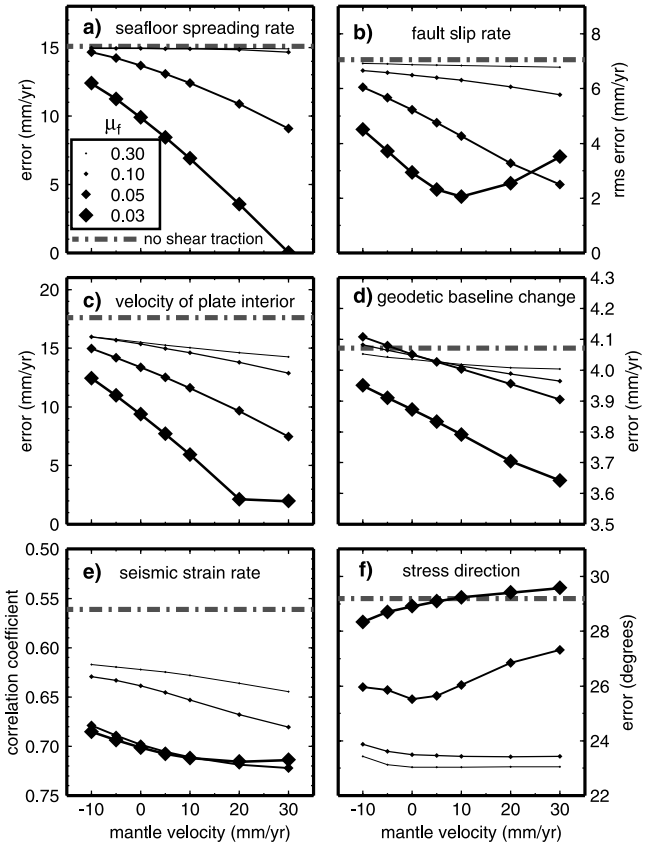

Figure 2. Model fit for different types of validation datasets as a function of the mantle velocity applied at 400 km depth (relative to Africa and positive eastward). Different curves in each panel represent different values of the fault friction coefficient. Dashed gray line represents results with fault friction coefficient of 0.03 and no shear traction on the base of the plate.

tion errors indicate better results with stiff models (Figure 2c). A possible explanation for this anomalous pattern is that many stress direction data used for the model validation actually come from wide plate boundary zones, and therefore represent deformation in the surrounding plates, and in particular, in the Cocos and Nazca subducting slabs, thus favoring stiff models, where convergence with these plates is more efficiently transferred to the Caribbean plate interior.

[11] We have also tried a set of models with velocity conditions for all boundaries from the global plate model NUVEL-1A [*DeMets et al.*, 1994]. Qualitative results remain unchanged in the sense that eastward basal shear tractions and low fault friction coefficient are still required. The best models with these lateral boundary conditions underestimate fault slip rates along the Caribbean-North America boundary and the seafloor spreading rate on the Cayman trough, and a better joint fit of datasets is obtained for models with North and South American boundary conditions derived from geodetic studies.

[12] Therefore, we can conclude that only models with low values of fault friction coefficient and east-directed mantle flow are successful. Low values of fault friction coefficients are also commonly found in global and regional studies [e.g., *Lachenbruch and Sass*, 1992; *Bird*, 1998; *Jiménez-Munt et al.*, 2001]. *Russo and Silver* [1994] proposed that mantle flow beneath the subducted Nazca slab is parallel to the trench and symmetrically diverted around South America beneath the Caribbean and Scotia plates. This would imply a predominantly east-directed mantle flow beneath these plates. This result is further supported by studies of anisotropy (SKS splitting) in NE Venezuela [*Russo et al.*, 1996], where fast directions are predominantly E-W, and the magnitude of the anisotropy is larger than the global average value. Eastward mantle flow might be enhanced by possible roll-back of the Atlantic slab subducting under the Lesser Antilles. This eastward drag on the Caribbean plate exerted by east-directed mantle flow is likely producing shear along the Caribbean-Americas boundaries. The fact that the magnitude of the seismic anisotropy in the northern Caribbean is smaller than in the southern boundary [*Russo et al.*, 1996] suggests that a constant mantle flow (in magnitude and direction) beneath the entire plate is an oversimplified assumption. However our results clearly show that the only successful neotectonic models are those with a significant eastward mantle drag,

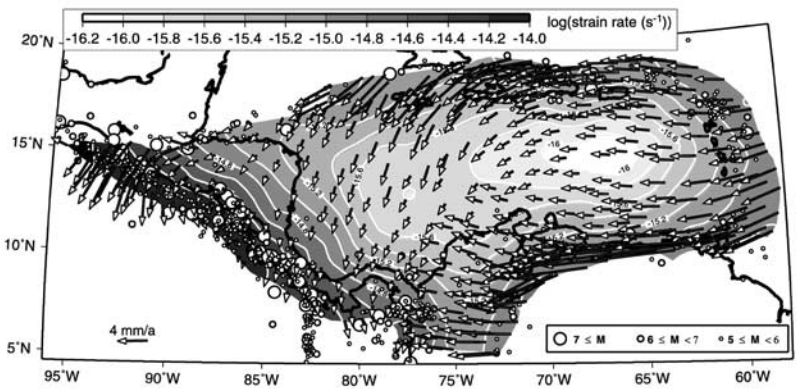

Figure 3. Strain rate distribution and horizontal velocity pattern in the interior of the Caribbean plate (arrows) predicted by a successful model with fault friction coefficient of 0.03 and mantle velocity at 400 km depth of 20 mm/yr. Earthquake epicenters from the *Engdahl and Villaseñor* [2002] catalog are shown as white circles, coded by magnitude. See color version of this figure in the HTML.

although the exact magnitude, direction, and depth of the flow cannot be determined.

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References

Audemard, F. A., M. N. Machette, J. W. Cox, R. L. Dart, and K. M. Haller (2000), Map and database of Quaternary faults in Venezuela and its offshore regions, *U.S. Geol. Surv. Open File Rep. 00-018*.

Bird, P. (1998), Testing hypotheses on plate-driving mechanisms with global lithosphere models including topography, thermal structure, and faults, *J. Geophys. Res.*, *103*, 10,115–10,129.

Bird, P. (1999), Thin-plate and thin-shell finite-element programs for forward dynamic modeling of plate deformation and faulting, *Comput. Geosci.*, *25*, 383–394.

Case, J. E., and T. L. Holcombe (1980), Geologic tectonic map of the Caribbean region, *U.S. Geol. Surv. Misc. Invest. Map I-1100*, *I-1100*.

Cowan, H. (1998), Map of Quaternary faults and folds of Panama and its offshore regions, *U.S. Geol. Surv. Open File Rep. 98-779*.

DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein (1994), Effect of recent revisions to the geomagnetic time scale on estimates of current plate motions, *Geophys. Res. Lett.*, *21*, 2191–2194.

DeMets, C., P. E. Jansma, G. S. Mattioli, T. H. Dixon, F. Farina, R. Bilham, E. Calais, and P. Mann (2000), GPS geodetic constraints on Caribbean-North America plate motion, *Geophys. Res. Lett.*, *27*, 437–440.

Dixon, T. H., F. Farina, C. DeMets, P. Jansma, P. Mann, and E. Calais (1998), Relative motion between the Caribbean and North American plates and associated boundary zones deformation based on a decade of GPS deformations, *J. Geophys. Res.*, *103*, 15,157–15,182.

Dziewonski, A. M., T.-A. Chou, and J. H. Woodhouse (1981), Determination of earthquake source parameters from waveform data for studies of global and regional seismicity, *J. Geophys. Res.*, *86*, 2825–2852.

Engdahl, E. R., and A. Villaseñor (2002), Global seismicity: 1900–1999, in *International Handbook of Earthquake and Engineering Seismology*, part A, edited by W. H. K. Lee et al., chap. 41, pp. 665–690, Academic, San Diego, Calif.

Jiménez-Munt, I., M. Fernàndez, M. Torné, and P. Bird (2001), The transition from linear to diffuse plate boundary in the Azores-Gibraltar region: Results from a thin-sheet model, *Earth Planet. Sci. Lett.*, *192*, 175–189.

Kong, X., and P. Bird (1995), SHELLS: A thin-plate program for modeling neotectonics of regional or global lithosphere with faults, *J. Geophys. Res.*, *100*, 2129–2131.

Lachenbruch, A. H., and J. H. Sass (1992), Heat flow from Cajon Pass, fault strength, and tectonic implications, *J. Geophys. Res.*, *97*, 4995–5015.

Liu, Z., and P. Bird (2002), North America is driven westward by lower mantle flow, *Geophys. Res. Lett.*, *29*(24), 2164, doi:10.1029/2002GL016002.

Lundgren, P. R., and R. M. Russo (1996), Finite element modeling of crustal deformation in the North America-Caribbean plate boundary zone, *J. Geophys. Res.*, *101*, 1317–1327.

MacMillan, D. S., and C. Ma (1999), VLBI measurements of Caribbean and South American motion, *Geophys. Res. Lett*, *26*, 919–922.

Mann, P., and K. Burke (1984), Neotectonics of the Caribbean, *Rev. Geophys.*, *22*, 309–362.

Mann, P., E. Calais, J.-C. Ruegg, C. DeMets, P. E. Jansma, and G. S. Mattioli (2002), Oblique collision in the northeastern Caribbean from GPS measurements and geological observations, *Tectonics*, *21*(6), 1057, doi:10.1029/2001TC001304.

Montero, W., P. Denyer, R. Barquero, G. Alvarado, and H. Cowan (1998), Map of Quaternary faults and folds of Costa Rica, *U.S. Geol. Surv. Open File Rep. 98-481*.

National Geophysical Data Center (2001), ETOPO2 Global 2' Elevations, www.ngdc.noaa.gov/mgg/image/2minrelief.html, Natl. Geophys. Data Cent., Boulder, Colo.

Pérez, O. J., R. Bilham, R. Bendick, J. R. Velandia, N. Hernández, C. Moncayo, M. Hoyer, and M. Kozuch (2001), Velocity field across the southern Caribbean plate boundary and estimates of Caribbean/South-American plate motion using GPS geodesy 1994–2000, *Geophys. Res. Lett.*, *28*, 2987–2990.

Pollack, H. N., S. J. Hurter, and J. R. Johnson (1993), Heat flow from the Earth's interior: Analysis of the global data set, *Rev. Geophys.*, *31*, 267–280.

Rosencrantz, E., M. I. Ross, and J. G. Sclater (1988), Age and spreading history of the Cayman trough as determined from depth, heat flow, and magnetic anomalies, *J. Geophys. Res.*, *93*, 2141–2157.

Russo, R. M., and P. G. Silver (1994), Trench-parallel flow beneath the Nazca plate from seismic anisotropy, *Science*, *263*, 1105–1111.

Russo, R. M., P. G. Silver, M. Franke, W. B. Ambeh, and D. E. James (1996), Shear-wave splitting in northeast Venezuela, Trinidad, and the eastern Caribbean, *Phys. Earth Planet. Inter.*, *95*, 251–275.

Trenkamp, R., J. N. Kellogg, J. T. Freymueller, and H. P. Mora (2002), Wide plate margin deformation, southern Central America and northwestern South America, CASA GPS observations, *J. South Am. Earth Sci.*, *15*, 157–171.

Weber, J. C., T. H. Dixon, C. DeMets, W. B. Ambeh, P. Jansma, G. Mattioli, J. Saleh, G. Sella, R. Bilham, and O. Pérez (2001), GPS estimate of relative motion between the Caribbean and South American plates, and geologic implications for Trinidad and Venezuela, *Geology*, *29*, 75–78.

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