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A new estimate for present-day Cocos-Caribbean plate motion: Implications for slip along the Central American volcanic arc

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Abstract. Velocities from 153 continuously-operating GPS sites on the Caribbean, North American, and Pacific plates are combined with 61 newly estimated Pacific-Cocos seafloor spreading rates and additional marine geophysical data to derive a new estimate of present-day Cocos-Caribbean plate motion. A comparison of the predicted Cocos-Caribbean direction to slip directions of numerous shallow-thrust subduction earthquakes from the Middle America trench between Costa Rica and Guatemala shows the slip directions to be deflected 10° clockwise from the plate convergence direction, supporting the hypothesis that frequent dextral strike-slip earthquakes along the Central American volcanic arc result from partitioning of oblique Cocos-Caribbean plate convergence. Linear velocity analysis for forearc locations in Nicaragua and Guatemala predicts 14±2 mm yr^{-1} of northwestward trench-parallel slip of the forearc relative to the Caribbean plate, possibly decreasing in magnitude in El Salvador and Guatemala, where extension east of the volcanic arc complicates the tectonic setting.

Introduction

Partitioning of oblique plate convergence into trench-normal subduction and arc-parallel shear plays an important role in transporting geologic terranes and deforming volcanic forearcs [*Jarrard*, 1986; *McCaffrey*, 1992]. The Cocos-Caribbean (CO-CA) segment of the Middle America subduction zone (Fig. 1), located between the diffuse Cocos-North America-Caribbean triple junction [*Guzman-Speziale et al.*, 1989] and the central Costa Rica deformed belt [*Marshall et al.*, 2000] appears to be a classic example of partitioning. Moderate-sized, upper-crustal earthquakes along the volcanic arc have occurred frequently during the past century, exacting a high death toll (~17,000) [*White and Harlow,* 1993]. Most of these earthquakes have accommodated trench-parallel, dextral strike-slip motion [*White*, 1991], consistent with northwestward transport of a forearc sliver relative to the Caribbean plate.

The goals of this paper are to use a geodetically-based estimate of CO-CA plate motion in conjunction with earthquake slip directions from the CO-CA segment of the Middle America trench to determine whether CO-CA motion is oblique to the trench and if so, whether partitioning of the oblique convergence occurs and what it implies for the present rate of forearc sliver motion [*Harland and White*, 1985]. The lack of reliable data with which to describe present-day Caribbean plate motion has precluded previous rigorous treatment of these questions. *Deng and Sykes* [1995] note that an angular discrepancy between the direction of motion of a geodetic site (Liberia) in western Costa Rica [*Dixon*, 1993] and a CO-CA convergence direction estimated from Caribbean plate earthquake slip directions and the NUVEL-1A plate motion model [*DeMets et al.*, 1994] is consistent with the occurrence of oblique convergence and strain partitioning; however, Liberia's motion is referenced to a single fixed site on the Cocos plate and thus cannot be meaningfully compared to a CO-CA direction derived from a kinematic model.

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Observations and angular velocities

A rigorous test for oblique CO-CA convergence and strain partitioning requires independent estimates of CO-CA motion and the direction of subduction along their plate boundary. The latter is determined from 124 thrust-faulting earthquakes that ruptured the shallow portions of the CO-CA subduction interface during the period 1963-2/2001 (Fig. 1). The horizontal slip directions of these earthquakes, which accommodate subduction beneath the forearc, constrain the direction of the Cocos plate relative to the forearc.

The new CO-CA angular velocity is constrained via closure of the Caribbean-North America-Pacific-Cocos plate circuit. GPS velocities of four sites on the Caribbean plate [*DeMets et al.*, 2000], 139 continuously-operating sites on the North American plate, ten continuous sites on the Pacific plate, and two azimuths from the Swan Islands transform fault [*DeMets et al.*, 2000] constrain the relative angular velocities of the Caribbean, North American, and Pacific plates. The Pacific-Cocos angular velocity is derived from the azimuths of three well-mapped transform faults that offset the Pacific-Cocos rise axis [*DeMets et al.*, 1990] and 61 new 0.78 Ma-average Pacific-Cocos seafloor spreading rates, to be described in a forthcoming paper.

The GPS geodetic velocities incorporate all measurements available through the end of March, 2001. GPS phase measurements are analyzed at the University of Wisconsin using GIPSY [*Zumberge et al.*, 1997], precise satellite orbits and clocks from Jet Propulsion Laboratory, and a standard point-positioning strategy. Daily free-network station coordinates are transformed to ITRF97 [*Boucher et al.*, 1999], yielding coordinate time series ranging from 2.0 to 7.5 years. Uncertainties in the GPS velocities are estimated using a model for white- and time-correlated noise in GPS coordinate time series [*Mao et al.*, 1999].

All angular velocities and their uncertainties (Table 1) are derived via minimization of the weighted, least-squares misfit to the GPS velocities and marine geophysical data,

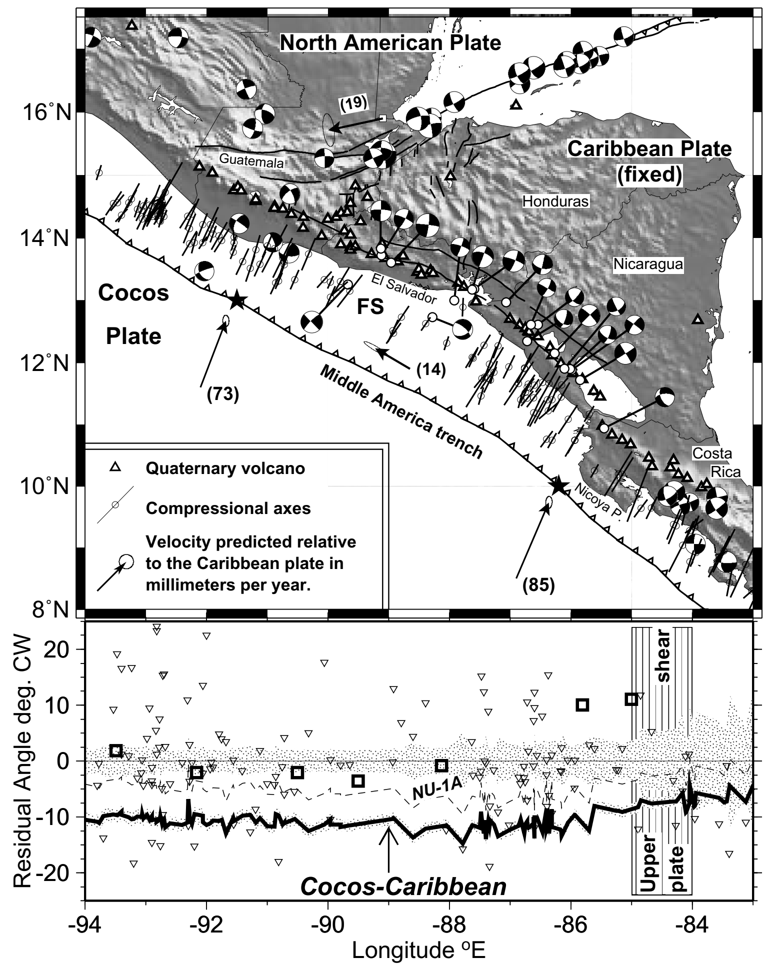

Figure 1. Upper - Location map, topography, and volcanotectonic setting of western Central America. Strike-slip earthquake focal mechanisms and compressional axes for shallow-thrust subduction earthquakes for the period 1963-2/2001 are from *Molnar and Sykes* [1969], *Dean and Drake* [1978], *Chael and Stewart* [1982], *Burbach et al.* [1984], *Guzman-Speziale et al.* [1989], *White and Harlow* [1993], and Harvard centroid moment tensor solutions. Compressional axis lengths are scaled to earthquake moments. Plate velocities and 95% uncertainties are relative to the Caribbean plate and are calculated from the model in Table 1. Rate for the forearc sliver (FS) is determined from Figure 2. Lower - Convergence directions predicted by the new and NUVEL-1A (NU-1A) Cocos-Caribbean angular velocities, directions normal to trench (squares), and horizontal slip directions of shallow-thrust subduction earthquakes (triangles) as residual angles from the direction predicted by the pole that best fits the earthquake slip directions from 94-85.5°W. Earthquake directions point toward the trench-normal direction and are rotated 10°±1° counter-clockwise from the Cocos-Caribbean convergence direction, indicating that oblique convergence is partitioned into trench-normal and trench-parallel components. The ~10° counter-clockwise rotation of slip directions east of ~85°W is consistent with the intersection at 85.5-84.5°W of the Central Costa Rica deformed belt [*Marshall et al.*, 2000] with the trench. Shaded areas show 1σ uncertainties.

subject to the requirement that the angular velocities satisfy plate circuit closure [*DeMets et al.*, 1990; *Ward*, 1990]. The average misfits of the angular velocities that best-fit the geodetic velocities are 1.1 and 1.3 mm yr^{-1} in the north and east components, with reduced chi-squared of 0.77. The geodetic velocities are thus fit slightly better than their estimated uncertainties. Reduced chi-square for the 61 spreading rates and five transform azimuths is 1.01, indicating that their average misfits equal their assigned uncertainties.

The closure-consistent angular velocities are well determined (Table 1) and agree well with published estimates. Pacific-Cocos velocities differ by no more than 2 mm yr^{-1} (1.5%) and 1° in rate and direction from those predicted by the 0.78-Ma-average model of *DeMets and Wilson* [1997]. Similarly, Pacific-North America and Caribbean-North America velocities differ by less than 1 mm yr^{-1} and 1.5° along their respective plate boundaries from velocities predicted by recent GPS-based models of *DeMets and Dixon* [1999] and *DeMets et al.* [2000]. The largest differences occur for the Cocos-North America plate pair, for which motion along the Middle America subduction zone is 6-7 mm yr^{-1} faster than predicted by NUVEL-1A and 2-5 mm yr^{-1} faster than predicted by *DeMets and Wilson* [1997].

Oblique subduction, strain partitioning, and slip along the volcanic arc

The new CO-CA angular velocity predicts convergence directions along the Middle America trench that are ~10° counter-clockwise from trench-normal (Fig. 1). Within the uncertainties, oblique convergence is strongly required. Convergence directions predicted by the NUVEL-1A CO-CA angular velocity differ from trench-normal by only 2-4° (Fig. 1), reflecting the fact that 56 earthquake slip directions from this segment of the trench were used in the NUVEL-1A model to constrain the CO-CA direction.

The evidence that the oblique convergence is fully partitioned is compelling. More than 90% (113) of the horizontal slip directions for the 124 shallow-thrust earthquakes described above are biased clockwise from the CO-CA convergence direction (Fig. 1), and the angular velocity that best-fits the 124 slip directions predicts average slip directions that are orthogonal to the observed trend of the trench (Fig. 1). The earthquakes thus record only the trench-normal component of motion. Significant evidence, including the existence of dextral-slip faults within the volcanic arc in Guatemala, El Salvador, and Nicaragua [*Carr*, 1976; *Weinberg*, 1992] and the concentration of earthquakes along the volcanic arc [*White and Harlow*, 1993], strongly suggests that the trench-parallel component of motion is concentrated along the volcanic arc.

Assuming the forearc moves parallel to the trench, the rate of strike-slip motion along the volcanic arc can be estimated from a linear velocity diagram (Fig. 2). The 10° angular difference between the directions recorded by earthquakes that occur beneath the forearc sliver and the rigid plate convergence direction implies respective northwestward slip rates of 14±2 mm yr^{-1} (1σ) and 14±2.5 mm yr^{-1} in Nicaragua and Guatemala relative to the stable Caribbean plate. The similar rates of northwestward translation at the two ends of the forearc imply that the forearc sliver is approximately rigid. Slip across the forearc faults in Guatemala and possibly El Salvador may be slower due to extension east of the forearc that siphons off an estimated 8 mm yr^{-1} of slip [*Burkart and Self*, 1985; *Guzman-Speziale*, 2001].

Complex tectonics associated with the Cocos-North America-Caribbean triple junction preclude identification of the leading edge of this sliver. The southeastern limit of the trailing edge is marked by a CCW rotation of subduction-related earthquake slip directions (Fig. 1) that marks where the central Costa Rica deformed belt intersects the trench just SE of the Nicoya Peninsula [*Marshall et al.*, 2000], although extension at the trailing edge may extend northwestward into southeastern Nicaragua.

The kinematic results thus confirm the model of strain

Table 1. Caribbean-Cocos-Pacific-North American plate angular velocities

Plate Pair	Angular Velocity			Error ellipse			
	Lat.	Long.	ω	ζ_1	ζ_2	θ	$\Delta\omega$
CA-NA	71.1	-123.4	0.199	12.1	1.5	40	0.017
CO-CA	21.9	-123.1	1.264	2.1	0.9	-8	0.057
CO-NA	28.1	-123.1	1.402	1.4	0.8	-13	0.051
CO-PA	38.2	-109.6	2.001	1.0	0.6	105	0.049
NA-PA	50.8	-71.6	0.744	1.1	0.6	1.5	0.007

First plate rotates counter-clockwise with respect to second. Latitude and longitude are in °N and °W, respectively. The rotation rate ω and its standard error $\Delta\omega$ are in units of degrees per million years. The 2-D standard error ellipse is specified by the semi-major and semi-minor axes ζ_1 and ζ_2, and θ, the angle of ζ_1 in degrees counter-clockwise from east. Units of ζ_1 and ζ_2 are in degrees. Abbreviations: CA, Caribbean; CO, Cocos; NA, North America; PA, Pacific.

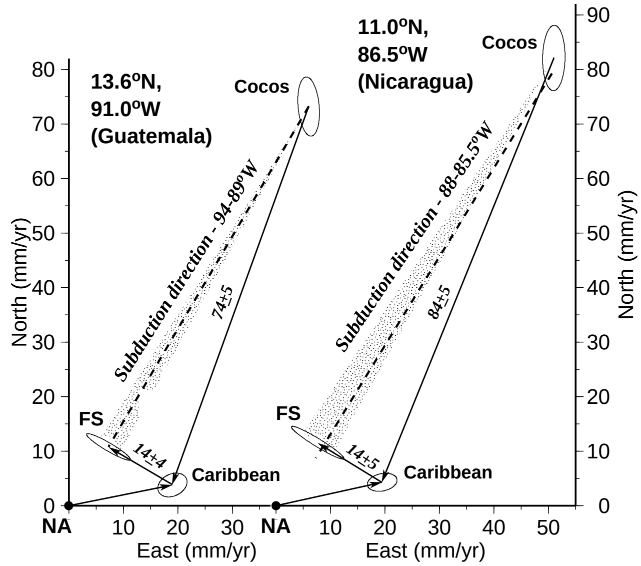

Figure 2. Cocos-Caribbean-North American (NA) plate linear velocities and trench-parallel forearc slip rates for two locations along the continental margin. Dextral, trench-parallel slip of 14±2 mm/yr of the forearc sliver (FS) relative to the Caribbean plate is inferred from the angle between the average shallow-thrust earthquake slip directions (dashed lines) and the Cocos-Caribbean convergence direction. Plate velocities are predicted using angular velocities in Table 1, rates are given in mm yr^{-1}, and uncertainties are 95%.

partitioning proposed by *Harlow and White* [1985] and constrain the rate of forearc slip. Geodetic observations in this region will eventually constrain the rate of forearc slip. The only continuous GPS site in the forearc, located in Managua, still has an immature coordinate time series (1.23 yrs as of 8/2001), but moves 10±4 mm yr^{-1} to the northwest (N57°W±20°) in a fixed Caribbean reference frame. Similarly, five GPS sites in the Costa Rican forearc have trench-parallel, northwest-directed velocity components of ~7 mm yr^{-1} [*Lundgren et al.*, 1999]. Interseismic elastic and post-seismic transient effects from forearc faults and the subduction interface, diffuse extension at the trailing edge of the forearc sliver, and partitioning of slip between multiple forearc faults must all be considered in interpreting these geodetic rates.

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