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Kinematics of the North American–Caribbean-Cocos plates in Central America from new GPS measurements across the Polochic-Motagua fault system

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[1] The Polochic-Motagua strike-slip fault system in Guatemala marks the on-land plate boundary between the North American (NA) and the Caribbean (CA) plates. GPS observations in 1999 and 2003 show that the far-field velocity across the system (NA-CA relative velocity) is ~20 mm/yr. This is significantly higher than the NUVEL-1A velocity but is consistent with the GPS based CA-NA velocity proposed by DeMets et al. (2000). The observations are modeled by a fault centered on the Motagua fault, locked at a depth of 20 km, with a slip-rate decreasing from eastern to central Guatemala from 20 to 12 mm/yr towards the NA-CA-Cocos triple junction. This decrease is accommodated by ~8 mm/yr of E-W extension in the westernmost part of CA south of the Motagua fault. About 10 mm/yr of dextral slip is observed across the Mid-American Volcanic Arc. The NA-CA-Cocos triple junction is thus a complex, ~400 km-wide wedge-shaped area. **Citation:** Lyon-Caen, H., et al. (2006), Kinematics of the North American–Caribbean-Cocos plates in Central America from new GPS measurements across the Polochic-Motagua fault system, *Geophys. Res. Lett.*, *33*, L19309, doi:10.1029/2006GL027694.

1. Introduction

[2] Crustal deformation in northern Central America is due to the relative motion of the Cocos (CO), Caribbean (CA) and North American (NA) plates. The boundary between CA and NA is marked by the complex left-lateral Polochic-Motagua Fault System (PMFS) (Figure 1). Prior to GPS-based geodesy, the CA-NA relative motion has been estimated from global plate kinematic models and earthquake slip vectors at plate boundaries (Nuvel-1a [*DeMets et al.*, 1994]). From GPS velocities at a few sites on the CA plate, *Dixon et al.* [1998] and *DeMets et al.* [2000] estimated the CA-NA relative motion to 18–20 mm/yr, about twice the Nuvel-1a estimate.

[3] In 1999 and 2003 we measured a 16 sites geodetic network in Guatemala using GPS. We present the analysis of the two-epochs GPS data. They provide the first direct measurement of the CA-NA relative velocity in Central America and reveal the complex deformation pattern in Guatemala due to the NA-CA-CO triple junction, across the PMFS, the North-South grabens south of it and the Mid-American volcanic arc (MAVA).

2. The Polochic-Motagua Fault System

[4] The PMFS extends along ~400 km from the Caribbean Sea to the east, to the Pacific Coast to the west (Figure 1). It is composed of three arcuate, sub-parallel, major left-lateral strike-slip faults: the Polochic, Motagua, and Jocotan faults, from north to south, respectively. A series of active N-S grabens are located south of the Motagua fault (MF) and north of the MAVA associated with the CO-CA subduction.

[5] This major transform boundary extends seaward to the east over more than 2000 km, through the Caribbean Sea up to the Puerto-Rico subduction trench (Figure 1).To the west, offshore southwestern Mexico, the connection of this active fault system with the Middle American trench remains poorly understood [e.g., *Plafker*, 1976; *Burkart*, 1983].

[6] The Polochic fault (PF) can be traced for almost 350 km from the Pacific Coastal Plain to the west to the Neogene pull-apart basin of Izabal Lake to the east. Then, it connects either with the MF or directly with the Swan fault offshore (Figure 1). The MF extends over 300 km on land and connects offshore to the Swan fault and the Cayman Trough to the east. Its western trace is masked beneath the late Cenozoic volcanics of the MAVA. The southernmost fault, the Jocotan fault (JF), extends about 200 km in Honduras and eastern Guatemala.

[7] Both the PF and MF show evidence of activity in their morphology. *Schwartz et al.* [1979] estimated a maximum Quaternary slip rate of 6 mm/yr for the MF based on the analysis of morphological features offset by the fault (alluvial terraces, fans and streams). Offsets of alluvial terraces and rivers, associated with the activity of the PF, have also been described [*Schwartz et al.*, 1979; *Erdlac and Anderson*, 1982; *Burkart et al.*, 1987]. No clear evidence of

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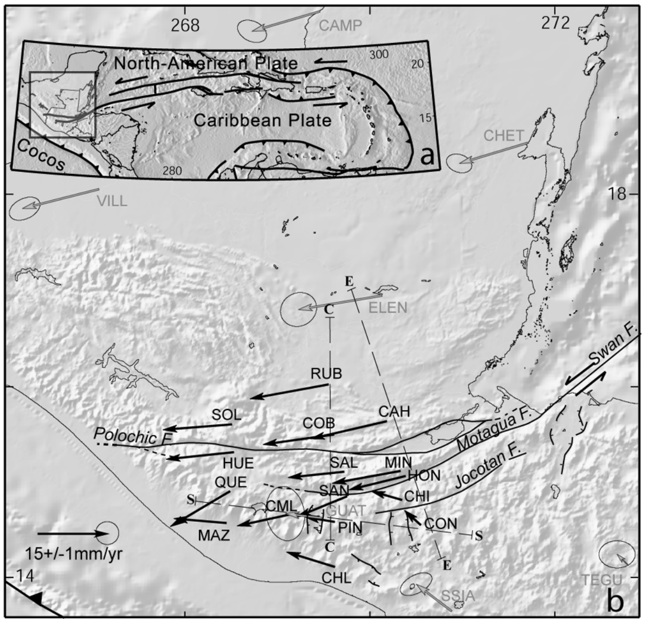

Figure 1. (a) Plate tectonics setting of the Caribbean. (b) Tectonic setting and topography of Northern Central America. Black lines outline active faults. ITRF2000 velocities at GPS sites in Caribbean plate reference frame obtained from the 1999 and 2003 campaigns (black arrows) and velocities from permanent sites (grey arrows [*Marquez-Azua and DeMets*, 2003; C. DeMets, personal communication, 2004]). When not drawn error ellipses are fixed to ±2 mm/yr (see text for explanation). Dashed lines show location of profiles E, C and S of Figure 2 and auxiliary material Figures S1 and S2.

Quaternary activity has been reported along the JF [*Schwartz et al.*, 1979; *Gordon and Muehlberger*, 1994].

[8] Large historical earthquakes and instrumental seismicity have been documented along the PMFS. The MF ruptured along 230 km during the February 4, 1976 (Ms = 7.5) earthquake with a mean slip of 2 m [*Plafker*, 1976]. This earthquake also reactivated the northwestern part of the Guatemala City graben. Two events of magnitude 7 or more have been reported on the western and eastern segments of the PF in 1816 and 1785, respectively [*White*, 1985]. The Ms = 8, 1856 event in Honduras is probably associated with the offshore extension of the PMFS [*Sutch*, 1981]. Large historical earthquakes have also been reported in the JF area in Honduras: the 950–1000 earthquake, a candidate for the destruction of the Copan Maya site [*Kovach*, 2004], and the Ms = 6.2, 1934 event [*White and Harlow*, 1993; *Kovach*, 2004]. However, it is unclear whether these events were associated with the JF itself or with the N-S grabens just south of it.

3. GPS Network and Data Processing

[9] Our geodetic network consists of 16 sites located along three N-S trending profiles, covering the central part of Guatemala (Figure 1). It allows deformation measurements across the Polochic, Motagua and Jocotan faults, the N-S grabens and the MAVA south of these faults. This network was measured in February 1999 and 2003. Five permanent GPS stations have been installed in Guatemala, Salvador and Honduras since 2000 and complement our network (Figure 1).

[10] Both GPS campaigns were carried out using eight Ashtech receivers (Z12 and ZXtrem) with Choke-Ring and Geodetic IV antennas. In 2003, four additional Trimble 5700 receivers with Zephyr antennas were used. Two sites (COB and PIN, Figure 1) were occupied continuously during 8 and 9 days in 1999 and 2003, respectively. Other sites were measured during at least 2 daily sessions of 12 h to 24 h. The recording interval was set to 30 seconds and the elevation mask to 10°.

[11] Our GPS data together with selected IGS stations data were processed using the GAMIT software [*King and Bock*, 2002] to produce daily unconstrained solutions. IGS earth rotation parameters and precise orbits were held fixed. Daily solutions were then stabilized in the ITRF2000 reference frame with GLOBK [*Herring*, 1998]. Seven IGS stations were used to tie the solution to the ITRF2000. Velocities in ITRF2000 (auxiliary material Table S1[1]) were then transformed into a CA-fixed reference frame by rotating them about the most recent CA/ITRF2000 pole determined by C. DeMets (personal communication, 2004) (Figure 1).

[12] We obtained averaged baseline repeatabilities for the north, east, up components of 2.5 mm, 3.5 mm and 7 mm, respectively, in 1999, and 3.2 mm, 8.3 mm and 13.5 mm, respectively in 2003. Formal errors from GLOBK on the station coordinates are about half. As only 2 epochs of measurements were available, we set errors on the station positions by multiplying the formal errors by a scaling factor (for each component, the ratio of the mean repeatability by the mean formal error). Uncertainties on velocities were obtained by dividing the L2 norm of uncertainties on station coordinates of 1999 and 2003 by the time span between measurements. This leads to uncertainties on horizontal velocities of about ±2 mm/yr.

4. Coseismic and Subduction-Related Deformation

[13] In order to interpret the GPS results in terms of regional deformation associated with the PMFS, we quantified (1) the coseismic deformation resulting from regional earthquakes which occurred between the two campaigns, and (2) the upper plate CA deformation due to coupling at the CO-CA subduction interface.

[14] Cumulative displacements at our GPS sites induced by 7 regional earthquakes (Mw: 5.2–7.7, depth: 10–60 km, see auxiliary material Tables S2 and S3), range from 1 to 12 mm (maxima at CON and CHI sites due to the Mw = 7.7 January 13 2001, Salvador earthquake). They were subtracted from measured displacements during data processing with GAMIT-GLOBK. Differences between corrected and uncorrected velocities are less than 2 mm/yr, within the estimated uncertainties of the GPS velocities. In the following we use these corrected velocities (Figure 1 and auxiliary material Table S1).

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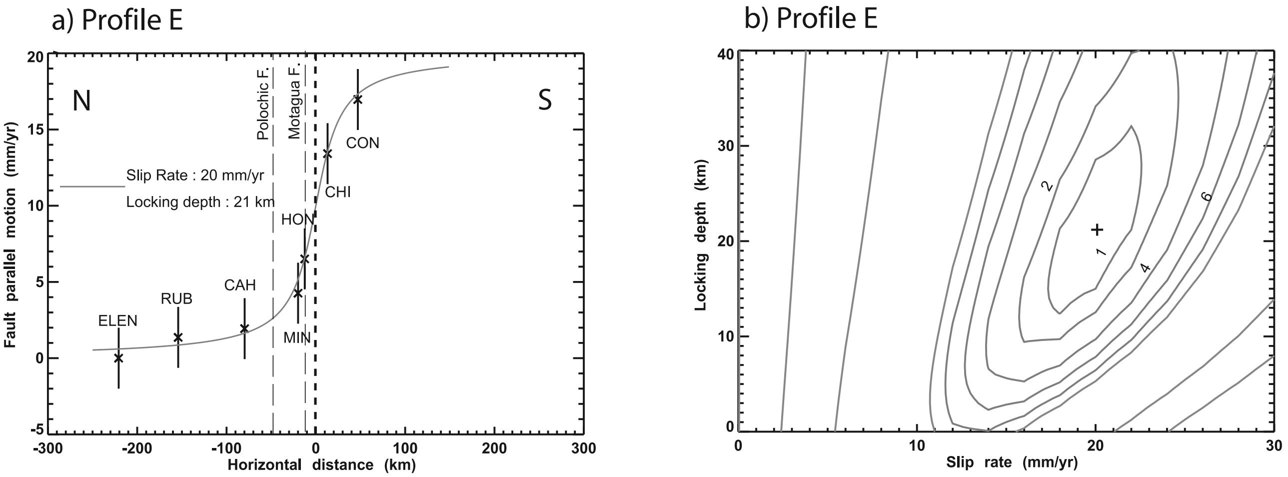
[1] Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2006gl027694. Other auxiliary material files are in the HTML.



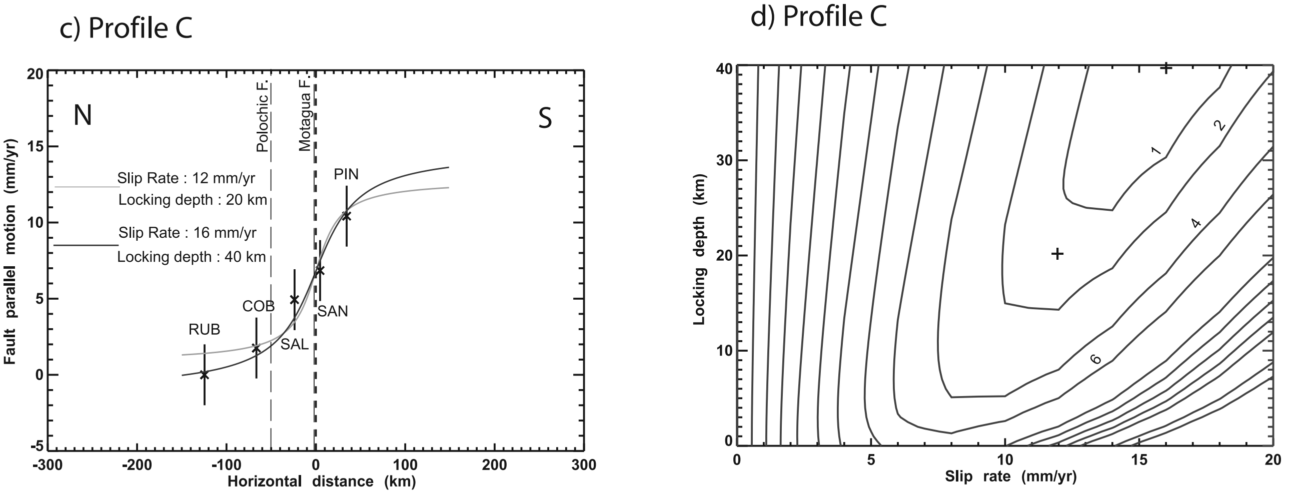


Figure 2. (a) ITRF2000 velocities projected onto profile E and locked fault model corresponding to minimum χ^2 (slip-rate 20 mm/yr, locking depth 20 km). Black dashed vertical line indicates location of inverted fault, grey dashed lines the mean trace of Polochic and northern Motagua faults. (b) Contour plots of the χ^2 statistic for the slip rate and locking depth on the Motagua fault tests, the position of the fault being fixed. Small cross indicates the parameters used in Figure 2a. (c) Same as Figure 2a for profile C showing two fault models with locking depths of 20 and 40 km and corresponding slip-rates of 12 and 16 mm/yr, respectively. (d) Same as Figure 2b for profile C. Two small crosses indicate parameters used in Figure 2c.

[15] Estimate of the Caribbean plate deformation due to coupling on the CO-CA subduction interface is obtained using the back-slip dislocation model of *Savage* [1983]. We used a 30° north dipping interface extending from the trench to a depth of 80 km (based on *Engdahl and Villasenor* [2002] relocated catalogue), a N120°E oriented trench and a CO-CA N20° relative velocity of 73 mm/yr [*DeMets*, 2001]. Simulations with various locking depths indicate that even a locking depth as small as 25 km induces velocities of 8–10 mm/yr in a NE direction, at the coastal sites (MAZ, CHL, and SSIA, Figure 1). Such large effects are not present in the observed velocity vectors at these sites. All are mainly orthogonal to the subduction direction with a component parallel to the subduction direction of 0–3 mm/yr only, and in opposite sense (SW) to the one expected. Given the uncertainties on our velocities, this suggests that coupling is too low to be detected in our data. This agrees with *Pacheco et al.'s* [1993] estimate of seismic coupling, of less than 0.2 in this area, based on the past 90 years of seismicity. We thus neglect coupling in the following interpretations.

5. Velocity Across the Polochic-Motagua Fault System

[16] In the CA-fixed reference frame, the velocity of ~2 mm/yr at CON, comparable within uncertainties to that of TEGU site, suggests that CON belongs to the stable CA plate (Figure 1). The similarity of RUB, ELEN, CHET and CAMP velocities, indicates that RUB moves as part of the NA plate (or of the Yucatan block [*Marquez-Azua and DeMets*, 2003]). Thus, the velocity of RUB, ~18mm/yr, gives a first order estimate of the NA-CA relative velocity. To better quantify this velocity and understand how the deformation is accommodated within the PMFS, we analyze the velocities projected along two N-S profiles perpendicular to the PF and MF faults (Figures 2a and 2c). The third, westernmost, profile (SOL, HUE, QUE) is too short and will be discussed in a later

study merging data from Guatemala and Chiapas area (A. Franco et al., manuscript in preparation, 2006). The fault-parallel velocities along the two profiles, typical of interseismic loading on a locked fault zone, are modeled using an infinitely long vertical strike-slip fault embedded in an elastic medium [*Savage and Burford*, 1973]. We model the fault zone by a single fault and invert for the locking depth, the interseismic velocity, and the location of the fault trace using the reduced χ^2 statistic approach as described by *Calais et al.* [2002]. The best fit on the eastern profile E (Figures 2a and 2b) is obtained for a fault centered on the southern branch of the MF, which ruptured in 1976, slipping at 20 mm/yr below a locking depth of 21 km. The central profile C (Figures 2c and 2d) can be fitted with locking depths ranging from 40 to 20 km and slip-rates at depth ranging from 16 to 12 mm/yr. Given the density of points on profile C, lower than on profile E, the slip-rate/locking depth trade-off and the uncertainties on the velocities (±2 mm/yr), we favor a model leading to a consistent 20 km locking depth for both profiles. On profile C, this corresponds to an interseismic velocity of only 12 mm/yr. As discussed below, this velocity decrease from east to west is consistent with the observed regional E-W extension south of the MF.

[17] Although the PF shows clear signs of recent activity [e.g., *Burkart*, 1978; *Schwartz et al.*, 1979; *White*, 1985], a simple model of loading of the MF alone is enough to explain the GPS data. To quantify the maximum slip-rate on the PF allowed by our GPS results, we investigated a 2-fault model, exploring various locking depths and slip rates on the two faults (auxiliary material Figure S1). This modeling suggests that no more than ~5 mm/yr could be accommodated on the PF. Whether this results from the oversimplification of our model, from the limited spatio-temporal resolution of our data or indicates a true low interseismic velocity on the PF, is unclear.

6. E-W Extension in Central Southern Guatemala

[18] Our GPS data allow to quantify the E-W extension across the grabens located south of the PMFS and north of the MAVA, in the westernmost part of the CA plate. The E-W profile, perpendicular to the N-S grabens (profile S, Figure 1, auxiliary material Figure S2), shows an extension of ~8 mm/yr accommodated over 200 km between sites QUE and CON, but mostly absorbed between sites PIN and CML across the Guatemala City graben. Based on moment tensor summation of a few events, *Guzman-Speziale* [2001] estimated the E-W extension in Honduras and Guatemala to be 2–15 mm/yr.

[19] The westernmost part of the CA plate, between the MF and the MAVA, is thus a wedge-shaped area of significant E-W extension, part of the complex NA-CA-CO triple junction. This extension is consistent with the existence of N-S trending Late Cenozoic grabens in southern Guatemala [e.g., *Williams et al.*, 1964; *Muehlberger and Ritchie*, 1975; *Plafker*, 1976]. It implies that slip-rate decreases along the PMFS from east to west.

7. Slip Along the Middle American Volcanic Arc

[20] GPS sites MAZ, CHL and SSIA located south of the MAVA on the forearc sliver, indicate a consistent right lateral movement of ~10 mm/yr relative to TEGU on the stable CA plate (Figure 1). This suggests that the forearc sliver in Guatemala behaves as a rigid block, as also observed along the Pacific Coast in Costa Rica and Nicaragua. This dextral slip is consistent with previous field observations [*Carr*, 1976] and fault plane solutions [*White and Harlow*, 1993]. It also agrees with the predicted 14.2 mm/yr dextral movement between the forearc and stable CA [*DeMets*, 2001]. Such relative motion may result from slip partitioning at the Middle American trench, due to the slightly oblique subduction of the CO plate under the CA plate [*DeMets*, 2001].

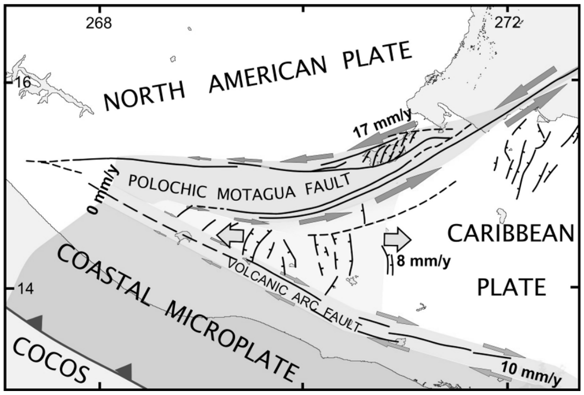


Figure 3. Proposed kinematic model of NA-CA-CO triple junction. See text for discussion.

8. Discussion: The North America–Caribbean-Cocos Triple Junction

[21] Our GPS data allow us to characterize the present day deformation within the NA-CA-CO triple junction area (Figure 3). At the CA-NA plate boundary, GPS velocities along two 200 km long profiles can be modeled using a single locked fault centered on the MF, slipping at depth at 20 mm/yr near longitude 270.5°E. This confirms the 18–20 mm/yr GPS-based CA-NA rate proposed by *DeMets et al.* [2000].

[22] We show that the CA-NA velocity in Guatemala decreases westwards from 20 to 12 mm/yr near longitude 269.5°E. This is explained by the 8 mm/yr E-W extension observed in the western part of the CA plate, wedged between the MF and the MAVA (Figure 3).

[23] The forearc sliver south of the MAVA seems to behave as a microplate (Central American coastal microplate, Figure 3), as observed in Costa Rica, Nicaragua and Salvador, with a 10 mm/yr dextral motion with respect to stable CA. This may be due to slip partitioning, although the inferred low coupling at the CO-CA subduction interface in Guatemala and Salvador should reduce stress transfer and partitioning as well.

[24] The classical definition of the NA-CA-CO triple junction is the intersection between the PMFS and the Middle American trench in the Gulf of Tehuantepec, offshore south-eastern Mexico [*White and Harlow*, 1993]. We show that the triple junction is more complex and is distributed over a wedge-shaped, 400 km-wide area (Figure 3). This kinematic model is entirely consistent with

that proposed by *Plafker* [1976]. Integration of this GPS data set with GPS data in southeastern Mexico and Central America is presently being conducted to refine the model.

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