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

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Abstract. 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. 2003-1999 GPS observations show that the far-field velocity across the system (NA-CA relative velocity) is 17-20 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 east to central Guatemala from 20 to 12mm/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, wedge-shaped area, extending over ~ 400 km

1. Introduction

Crustal deformation in Central America is due to the relative motion of the Cocos (CO), Caribbean (CA) and North American (NA) plates (Fig. 1a). The boundary between CA and NA is marked by the complex left-lateral Polochic-Motagua Fault System (PMFS) (Fig. 1b). Prior to GPS based geodesy, the CA-NA relative motion was estimated from global plate kinematics models and earthquakes slip vectors at plate boundaries (Nuvel-1a; DeMets et al., 1994). From GPS velocities at 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.

In 1999 and 2003 we measured a 16 points geodetic network in Guatemala using GPS. We present here 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 Polochic-Motagua transform boundary, the N-S grabens south of it and the Mid-American volcanic arc (MAVA).

2. The Polochic-Motagua fault system

The PMFS extends along ~ 400 km from the Caribbean Sea to the east, to the Pacific Coast to the west (Fig. 1). It is composed of three arcuate, sub-parallel, major left-lateral srike-slip faults: from north to south, the Polochic (or Polochic-Chixoy), the Motagua, and Jocotan (or Jocotan-Chamelecon) faults. A series of active N-S grabens are located south of the Motagua fault and north of the volcanic arc associated with the CO-CA subduction.

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 (Fig. 1a). The connection of this active fault system with the Middle American trench offshore southwestern Mexico remains poorly understood (e.g. Plafker, 1976; Burkart, 1983; Burkart and Self, 1985).

The Polochic Fault can be traced for almost 350 km from the Neogene pull-apart basin of Izabal Lake at the eastern end, to the Pacific Coastal Plain to the west. Further east, it connects either with the Motagua fault or directly with the Swan fault offshore. The Motagua fault 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, extends about 200 km in Honduras and eastern Guatemala.

Both the Polochic and Motagua faults show evidences of activity in their morphology. Schwartz et al. (1979) estimated a maximum quaternary slip rate of 6 mm/yr for the Motagua fault based on 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 Polochic Fault, have also been described (Burkart, 1978; Schwartz et al., 1979; Erdlac and Anderson, 1982; Burkart, 1983; Deaton and Burkart, 1984; Burkart et al., 1987). No clear evidence of Quaternary activity has been reported along the Jocotan Fault (Schwartz et al., 1979, Gordon and Muehlberger, 1994).

Large historical earthquakes and instrumental seismicity have also been documented. The Motagua Fault ruptured along 230 km during the February 4, 1976 (Ms=7.5) earthquake with a mean slip of 2 m and a maximum observed surface slip of 3 m (Plafker, 1976; Fig. 1b). This earthquake also reactivated the northwestern part of the Guatemala City graben (Fig. 1b). Two events of magnitude 7 or more have been reported on the western and eastern segment of the Polochic fault 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 are documented on the Jocotan Fault area in Honduras: the 950-1000 earthquake which most likely destroyed 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 Jocotan fault itself or with the N-S grabens located to the south.

3. GPS network and data processing

Our geodetic network consists of 16 points located along 3 N-S trending profiles, covering the central part of the PMFS in Guatemala (Fig. 1b and 2). It allows measurements of the deformation across the Polochic, Motagua and Jocotan strike-slip faults, the N-S grabens south of these faults, and the MAVA. This network was installed and measured in February 1999 and reoccupied in February 2003. Five permanent GPS stations have been installed in Guatemala since 2000 and complement our network (Fig. 1b).

Both GPS campaigns were carried out using 8 Ashtech receivers (Z12 and ZXtrem) with Choke-Ring and Geodetic antennas. In 2003, 4 additional Trimble 5700 receivers with Zephyr antennas from the IGN of Guatemala were used. Two sites (COB and PIN, Fig. 2) were occupied continuously during 8 and 9 days in 1999 and 2003, respectively. Other sites were measured simultaneously during at least 2 daily sessions of 12 to 24 h. The recording interval was set to 30s and the elevation mask to 10º.

GPS data were processed using GAMIT (King et al., 1993), together with IGS global solutions from SOPAC, 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 ITRTF2000 (table 1) were then transformed into a CA-fixed reference frame by rotating them about the most recent CA/ITRF2000 pole determined by DeMets (2004, personal communication) (Fig. 2) .

Within our network, 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 then obtained by dividing the L2 norm of uncertainties on station coordinates of 1999 and 2003 by the elapsed time between measurements. This leads to uncertainties in the horizontal velocities of about ±2 mm/yr.

4. Coseismic and subduction-related deformation

Before interpreting the GPS results in terms of regional deformation associated with the PMFS, we quantified the co-seismic deformation resulting from regional earthquakes that occurred between the two campaigns, and the upper plate CA deformation due to coupling at the CO-CA subduction interface.

Cumulative displacements at our GPS points induced by 7 selected regional earthquakes (Mw: 5.2-7.7, depth: 10 - 60 km), range from 1 to 12 mm (maximum at CON and CHI sites due to the Mw=7.7 January 13 2001, Salvador earthquake). They were substracted from our velocities during data processing with GAMIT-GLOBK. Differences between corrected and original velocities are less than 2 mm/yr, within the estimated uncertainties of the GPS velocities. We use these corrected velocities (Fig. 2 and Table 1).

Estimates 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 80 km depth (based on Engdahl's relocated catalogue), a N120°E oriented trench and a CO-CA N20° relative velocity of 73 mm/yr (DeMets, 2001). Tests of 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, Fig. 2). Such large effects are not present in the observed velocities at these three sites, all essentially orthogonal to the subduction direction (Fig. 2) with a SW component parallel to the subduction direction of 0-3 mm/yr only. Given the uncertainties on our measurements, this suggests that coupling is too low to be detected in our data. This agrees with Pacheco et al.'s (1993) estimation of seismic coupling, less than 0.2 in the area, based on the last 90 years of seismicity. We thus neglect coupling in the following interpretations.

5. Velocity across the Polochic-Motagua fault system

In the CA-fixed reference frame, the velocity of ~2 mm/yr at CON (Fig. 2), comparable to that of TEGU site, suggests that CON belongs to the stable CA plate. Similarly, velocity at RUB is similar to that of ELEN, CHET and CAMP, indicating that RUB moves as part of the NA plate (or of the Yucatan block, Marquez-Azcua and DeMets, 2004). Thus, the velocity difference between sites RUB and CON (260 km apart, Fig. 2), 17-20 mm/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 first analyse the velocities projected along 2 N-S profiles perpendicular to the strike-slip faults (Fig. 3a to 3e). The fault parallel velocities along the profiles, typical of interseismic loading on a locked fault zone, are modeled using an infinitely long vertical strike-slip fault in an elastic medium (Savage and Burford, 1973). We first assume that the fault zone can be represented by a single fault and invert for the locking depth, the interseismic velocity, and the location of the fault trace. The best fit on the eastern profile E is obtained for a fault centered on the southern branch of the Motagua fault that ruptured in 1976, slipping at 20 mm/yr below a locking depth of 20 km (Fig. 3b-c-f). Profile C can be fitted with locking depths ranging from 40 to 20 km and slip-rates at depth ranging from 16 to 12 mm/yr (Fig. 3d-e-f). Given the lower density of points on profile C 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 Motagua fault.

Although the Polochic Fault shows clear signs of recent tectonic and seismic activity (e.g., Burkart, 1978; Schwartz et al., 1979; Erdlac and Anderson, 1982; Deaton and Burkart, 1984; White, 1985), a simple model of loading of the Motagua fault alone is enough to explain our GPS observations. To quantify the maximum slip-rate on the Polochic fault allowed by our GPS results, we investigated a 2-faults model, varying locking depths and slip rates on the two faults. This modeling suggests that no more than 2 mm/yr could be accommodated on the Polochic fault. Whether this results from the oversimplification of our model, from low interseismic velocity on the Polochic fault or from the limited spatio-temporal resolution of our data, is unclear.

6. E-W extension in Central Southern Guatemala

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, Fig. 3), shows an extension of ~8 mm/yr over 200 km between sites QUE and CON, mostly absorbed between sites PIN and CML across the Guatemala City graben (Fig. 3h-g).

Our GPS results show that the westernmost part of the CA plate is a wedge-shaped area of significant internal E-W extension located between the Motagua Fault and the MAVA, part of the complex NA-CA-CO triple junction. The observed extension is consistent with the geological observations of N-S trending Late Cenozoic grabens in southern Guatemala (Williams et al., 1968; Muehlberger and Ritchie, 1975; Plafker, 1976; Burkart and Self ,1985). It also implies that the observed slip-rate decreases along the PMFS from east to west (Fig. 3).

7. Slip along the Middle American Volcanic Arc

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 (Fig. 1b). 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 (White and Harlow, 1993). The observed dextral slip is consistent with previous field observations (Carr, 1976) and fault plane solutions (White and Harlow, 1993). It is also in agreement with the predicted 14.2 mm/yr dextral movement between the forearc and stable CA based on GPS data (Demets, 2001). Such relative motion is the likely result of slip partitioning at the Middle American trench due to the slightly oblique subduction of the Cocos plate under the Caribbean plate (White and Harlow, 1993; Demets, 2001).

The dextral component of slip decreases westward across the arc: from 10 mm/yr arc-parallel relative velocity between SSIA and CON or TEGU to ~ 4 mm/yr between CHL and PIN (Fig. 2). This is consistent with the E-W extension observed north of the MAVA.

Discussion and conclusion: the North America-Caribbean-Cocos triple junction

Our GPS measurements allow us to characterize the present day deformation within the NA-CA-CO triple junction area (Fig. 4). 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

Motagua fault, slipping at depth at 20 mm/yr near longitude 270.5°E. This rate confirms the 18-20 mm/yr GPS-based CA-NA rate proposed by Demets et al. (2000).

We show that the CA-NA relative 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 stable CA plate, wedged between the Motagua fault and the MAVA (Fig. 4).

The forearc sliver south of the MAVA seems to behave as a microplate (Central American coastal plate, Fig.4), as observed in Costa Rica, Nicaragua and Salvador, with a 10 mm/yr dextral motion with respect to stable CA. This is likely 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.

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 (Fig. 4). This kinematic model is entirely consistent with that proposed by Plafker (1976). The integration of this GPS data set with data in southeastern Mexico and central America must now be conducted to refine the model.

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Table 1: 1999-2003 GPS velocities in ITRF 2000

Site	Lat.,°N	Long., °E	Elevation (m)	Vn (1) (mm/yr)	Ve (2) (mm/yr)
CAH	15.605	270.182	336	-0.56	-5.42
CHI	14.779	270.348	1064	4.24	6.25
CHL	14.075	269.618	223	3.36	1.88
CML	14.638	269.196	1780	-1.93	-0.74
COB	15.464	269.611	1224	-0.13	-4.18
CON	14.517	270.548	1326	4.64	10.74
HON	15.030	270.385	208	0.23	0.06
HUE	15.282	268.531	1927	-0.37	-3.57
MAZ	14.537	268.450	276	1.85	-0.19
MIN	15.084	270.329	1701	0.48	-2.51
PIN	14.551	269.620	1785	1.79	6.00
QUE	14.871	268.486	2454	-6.66	-1.65
RUB	15.990	269.553	122	-0.77	-6.57
SAL	15.075	269.719	1029	0.48	-1.20
SAN	14.818	269.751	472	-3.12	1.38
SOL	15.571	268.506	3386	0.11	-4.08

(1): north component of velocity in ITRF2000

(2): east component of velocity in ITRF2000

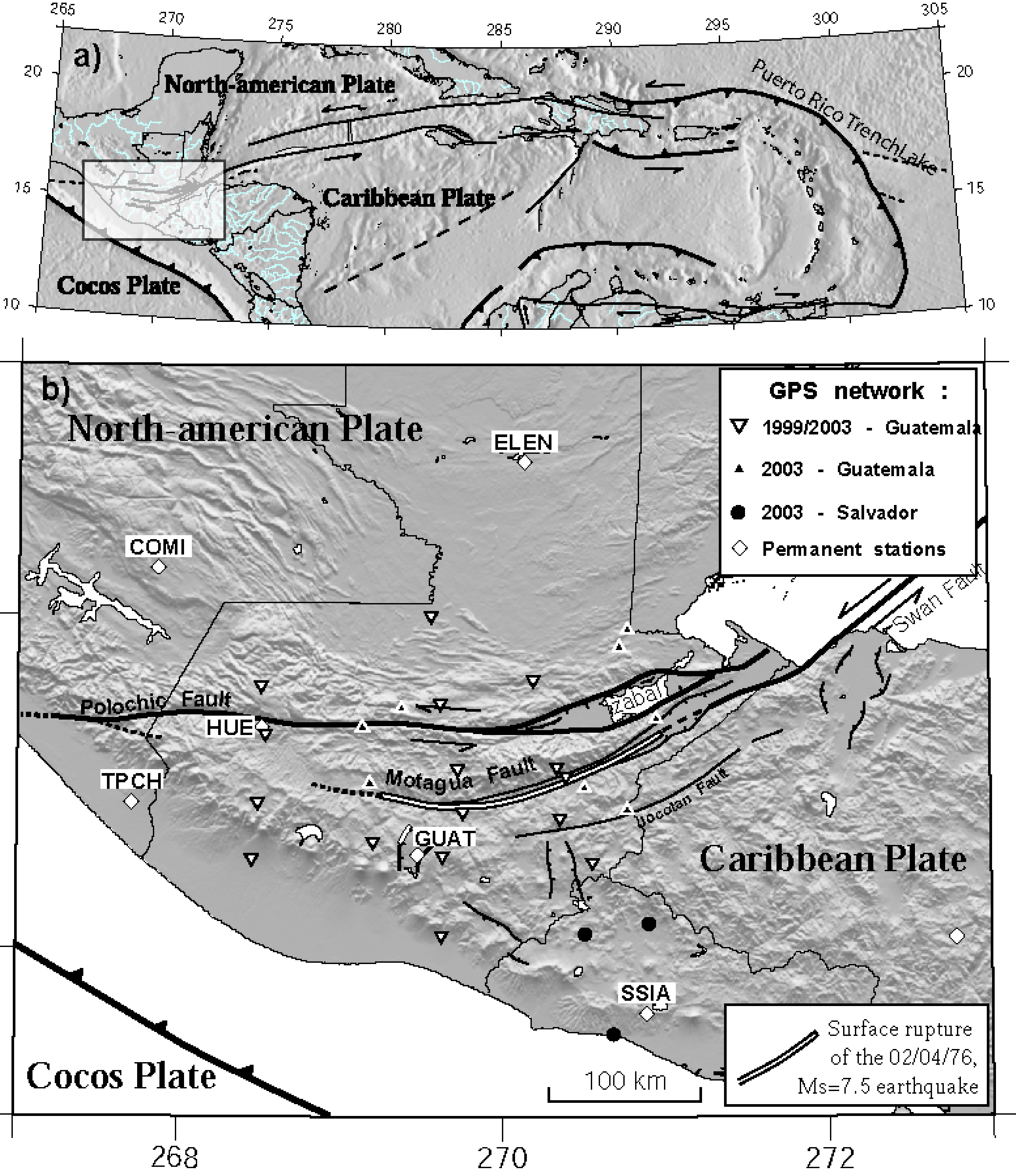
Figure captions

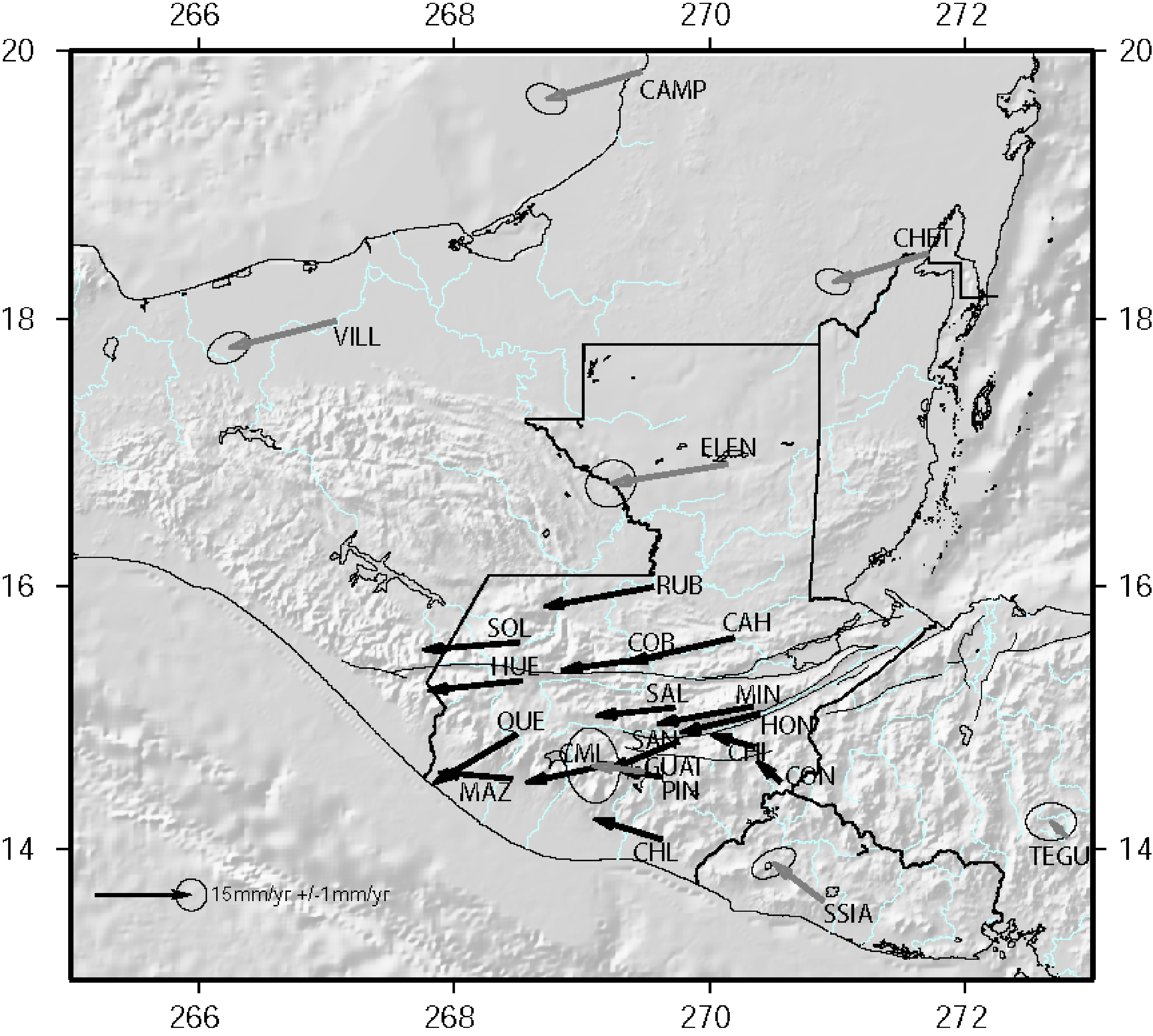
Figure 1. (a) Plate setting of the Caribbean. (b) Tectonic setting and topography of Northern Central America. GPS sites occupied in 1999 and 2003 and permanent GPS stations are shown. Black lines outline active faults. Surface rupture of the 1976 Guatemala earthquake is outlined in white (from Plafker, 1976).

Figure 2. ITRF2000 velocities 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, 2004; DeMets, personal communication).

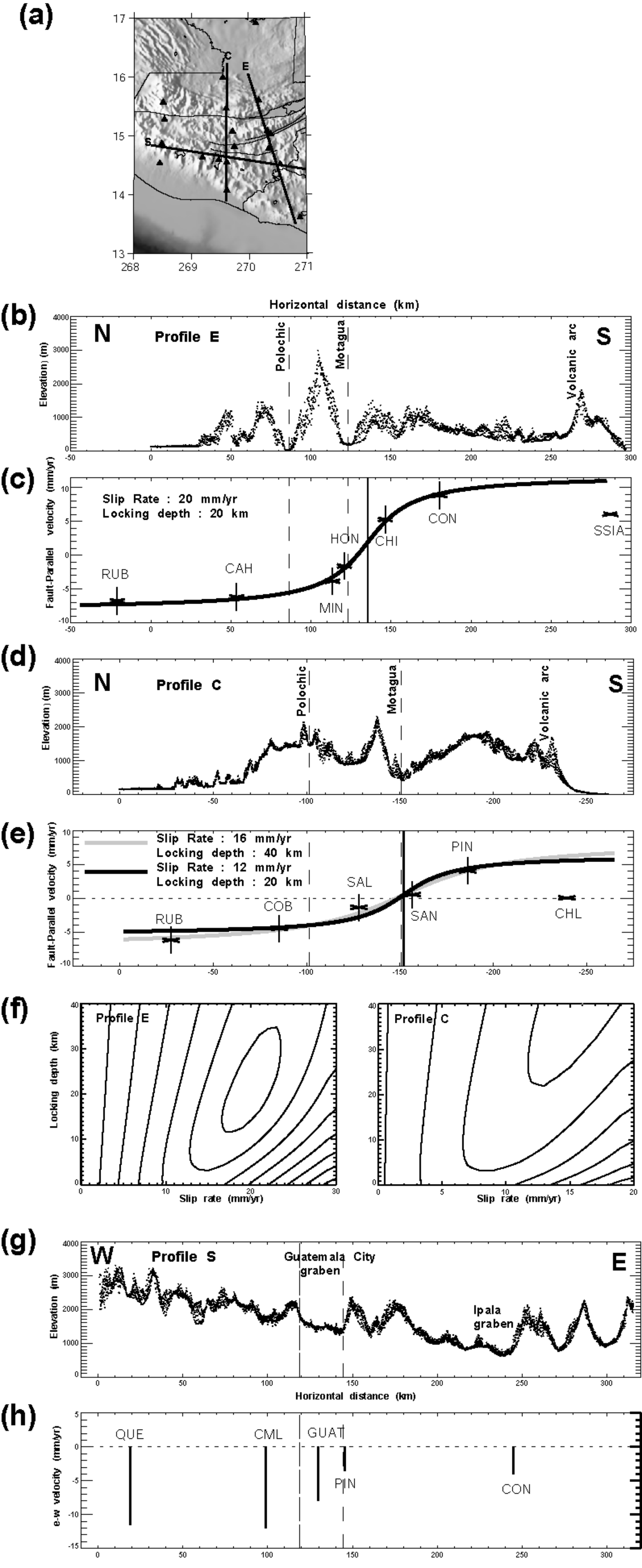
Figure 3. (a) Location map for profiles C, E and S. (b) Topography along profile E. (c) Fault-parallel ITRF2000 velocities projected onto profiles E and inverted locked fault model (slip-rate= 20 mm/yr, locking depth= 20 km). Black vertical line indicates location of inverted fault, dashed lines the mean trace of Motagua and Polochic faults. (d) Topography along profile C. (e) Same as (c) for profile C showing two fault models with locking depths of 20 and 40 km and corresponding slip-rates of 12 ad 16 mm/yr respectively. (f) Contour lines of RMS (every 1 mm/yr) from inversion of locking depth and slip-rate for profile E (left) and profile C (right), showing trade-off between slip rate and locking depth as discussed in the text. (g) Topography along profile S. (h) E-W projection of ITRF2000 velocities in the Caribbean plate reference frame.

Figure 4. Proposed kinematic model of NA-CA-CO triple junction. See text for discussion.

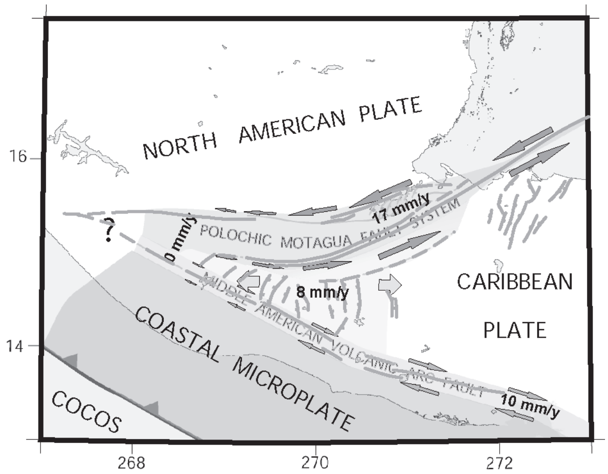

a)
North-american Plate
Caribbean Plate
Cocos Plate
Puerto Rico TrenchLake
265
270
275
280
285
290
295
300
305
20
15
10
b)
North-american Plate
Caribbean Plate
Cocos Plate
GPS network :
1999/2003 - Guatemala
2003 - Guatemala
2003 - Salvador
Permanent stations
ELEN
COMI
HUE
TPCH
GUAT
SSIA
Polochic Fault
Motagua Fault
Jocotan Fault
Swan Fault
Izabal
100 km
Surface rupture of the 02/04/76, Ms=7.5 earthquake
16
14
268
270
272



266
268
270
272
20
18
16
14
CAMP
CHET
VILL
ELEN
RUB
SOL
CAH
COB
HUE
SAL
MIN
QUE
HON
SAN
CML
CHI
GUAT
CON
MAZ
PIN
CHL
TEGU
SSIA
15mm/yr +/-1mm/yr



(a)
C
E
S
(b)
Horizontal distance (km)
N
Profile E
Polochic
Motagua
Volcanic arc
S
Elevation (m)
(c)
Fault-Parallel velocity (mm/yr)
Slip Rate : 20 mm/yr
Locking depth : 20 km
RUB
CAH
MIN
HON
CHI
CON
SSIA
(d)
N
Profile C
Polochic
Motagua
Volcanic arc
S
Elevation (m)
(e)
Fault-Parallel velocity (mm/yr)
Slip Rate : 16 mm/yr
Locking depth : 40 km
Slip Rate : 12 mm/yr
Locking depth : 20 km
RUB
COB
SAL
SAN
PIN
CHL
(f)
Profile E
Profile C
Locking depth (km)
Slip rate (mm/yr)
Slip rate (mm/yr)
(g)
W
Profile S
Guatemala City graben
Ipala graben
E
Elevation (m)
Horizontal distance (km)
(h)
e-w velocity (mm/yr)
QUE
CML
GUAT
PIN
CON



NORTH AMERICAN PLATE
16
17 mm/y
POLOCHIC MOTAGUA FAULT SYSTEM
?
0 mm/y
8 mm/y
CARIBBEAN
PLATE
MIDDLE AMERICAN VOLCANIC ARC FAULT
14
COASTAL MICROPLATE
10 mm/y
COCOS
268
270
272