Constraints from finite element modeling on the active tectonics of northern Central America and the Middle America Trench

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[1] We have developed an elastic finite element model in order to study the role of the different forces acting on the northwestern part of the Central American Volcanic Arc and the Chortis Block. We present synthetic focal mechanisms, maps of tectonic regime, and strain crosses to analyze the results. The models show that to achieve the observed state of stress on the volcanic arc, the arc must be modeled as a lithospheric weak zone. Also, the forces related to the eastward drift of the Caribbean plate must be higher than those related to the subduction of the Cocos plate. The coupling on the subduction interface must be low, with or without slip-partitioning due to the obliquity of the subduction at the trench. At Guatemala the western edge of the Chortis block is pinned against North America, even with low trench-normal forces, making the triple junction between the Cocos, North American, and Caribbean plates a zone of diffuse deformation. The extension in the western part of the Chortis block, from Guatemala to the Honduras depression, is explained by the geometry of the North American-Caribbean plate boundary and the direction of motion of the Caribbean plate with respect to North America. The direction of extension in the Chortis block is always E-W regardless of the magnitude of the applied forces, and the main part of the deformation is absorbed between the Ipala graben and the Honduras depression, both features being consistent with our models. **Citation:** Álvarez-Gómez, J. A., P. T. Meijer, José J. Martínez-Díaz, and R. Capote (2008), Constraints from finite element modeling on the active tectonics of northern Central America and the Middle America Trench, *Tectonics*, *27*, TC1008, doi:10.1029/2007TC002162.

1. Introduction

[2] The tectonics and geodynamics of northern Central America and the Middle America Trench have been subject of debate during the last decades, but no general consensus on the model to adopt has been reached. The last works on the subject show new results and constraints on the strain and deformation of the area by means of focal mechanism analysis [*Cáceres et al.*, 2005; *Guzmán-Speziale*, 2001; *Guzmán-Speziale et al.*, 2005] and GPS measurements [*DeMets*, 2001; *Lyon-Caen et al.*, 2006]. At the same time, new clues about the deformation of the volcanic arc and the influence of the Cocos subduction beneath the Caribbean plate appeared [*Corti et al.*, 2005; *Cowan et al.*, 2002; *Martínez-Díaz et al.*, 2004; *Rogers et al.*, 2002]. Some facts seem to be well established (e.g., the E-W extension of the Chortis block, the existence of a diffuse deformation area forming the North American-Cocos-Caribbean triple junction, the presence of a strike slip deformation corridor along the volcanic arc), but new questions arose and some of the old ones remain: Is there slip-partitioning at the trench? How could this influence the volcanic arc? How is the extension of the Chortis block generated? What is the influence of the subduction forces on the deformation of the volcanic arc? What produces the segmentation of the volcanic arc? In this work we contribute new constraints to these questions by means of numerical modeling of the state of stress and strain in northern Central America, analyzing the role of the trench forces, slip-partitioning, and the influence of the Caribbean drift on the deformation of the Chortis block and the volcanic arc. Finally a tectonic model including the latest results is presented. In this model the weakness of the volcanic arc is 1 order of magnitude lower than the neighboring lithosphere and the coupling of the subduction interface is low. The forces associated to the Caribbean drift are more important to the state of stress in the arc and the Chortis block than the forces due to the subduction of the Cocos plate.

2. Tectonic Setting

[3] Central America is the Pacific active margin of the Caribbean plate and forms since Pliocene time a large isthmus [*Kirby and MacFadden*, 2005] that connects south and North America. This isthmus can be divided into two parts in terms of its tectonic history and environment. Southern Central America geographically comprises Costa Rica, Panama, and northwestern Colombia, while the northern part comprises Nicaragua, Honduras, El Salvador, Guatemala and the southern part of México (Figure 1a). This division is explained tectonically by the different history of both areas. The southern area was built up as an intraoceanic magmatic arc in the Cretaceous to the southwest of its present position, while the northern area was formed as a continental active margin welded to the

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present Mexican active margin (for an extended explanation and discussion follow the debate about the evolution and formation of the Caribbean plate; some recent works are those of *Denyer et al.* [2006], *Meschede and Frisch* [1998], *Pindell et al.* [2006], and *James* [2006]).

[4] Our study area is centered on northern Central America, which is mainly constituted by the Chortis block, a continental wedge shaped crustal block whose characteristics are similar to the blocks of southern Mexico [*Case et al.*, 1984; *Malfait and Dinkelman*, 1972; *Pindell and Barret*, 1990; *Rogers*, 2003; *Wadge and Burke*, 1983] composed by a Paleozoic basement overlain by Mesozoic marine sediments and volcanic materials from the Pacific arc. The Central America volcanic arc extends from Guatemala to Costa Rica along the active Pacific margin, where the Cocos plate subducts beneath the Chortis block, the latter being part of the Caribbean plate (Figure 1b). The volcanic arc ends abruptly in the north, cut by the Polochic fault in

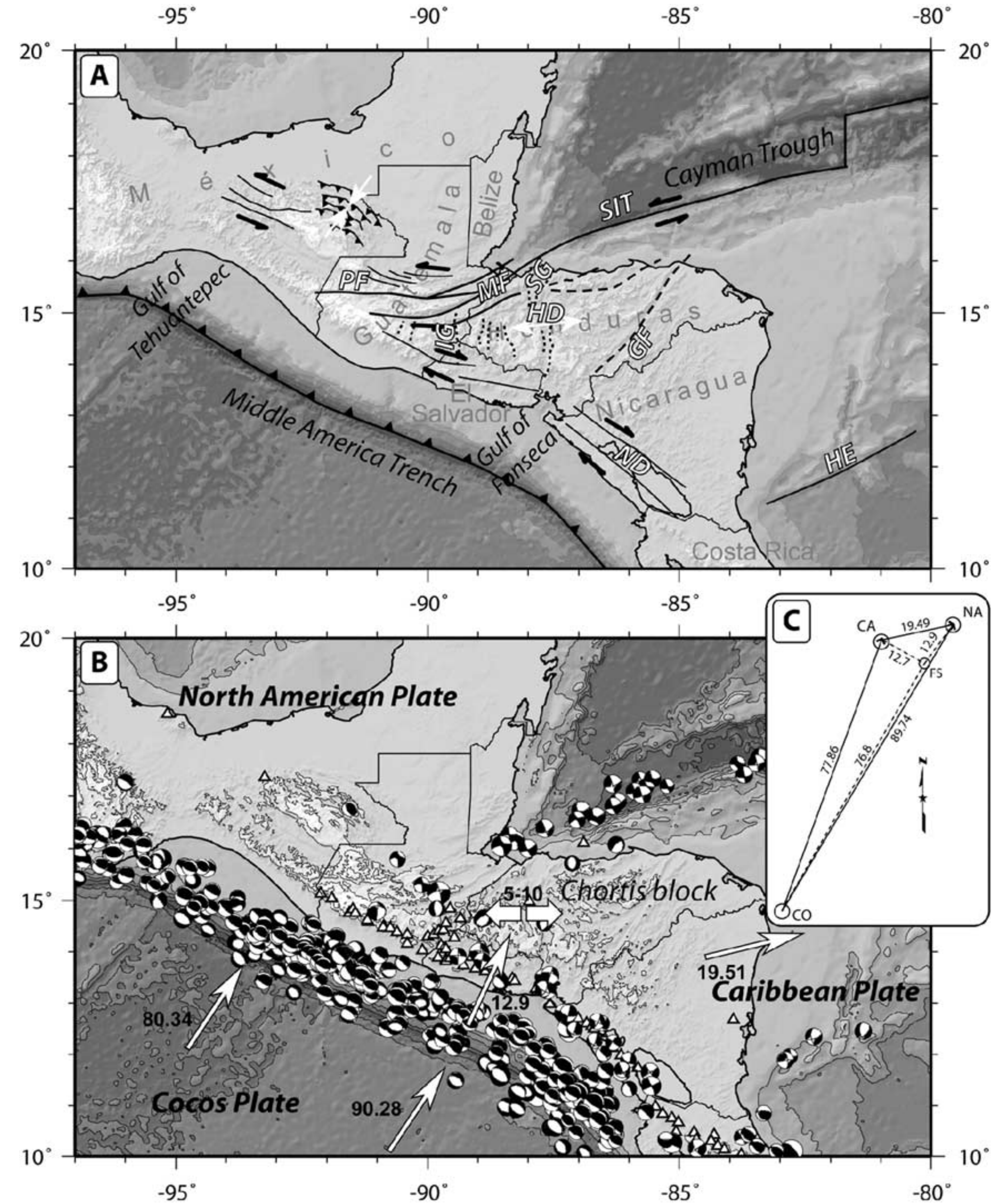

Figure 1

Guatemala, in the zone of the diffuse triple junction between the Cocos, Caribbean and North American plates [*Guzmán-Speziale et al.*, 1989; *Guzmán-Speziale and Meneses-Rocha*, 2000; *Lyon-Caen et al.*, 2006; *Plafker*, 1976]. This volcanic arc can be segmented on the basis of the distribution and characteristics of the volcanic edifices as was done by *Stoiber and Carr* [1973], but we can divide it in at least three main segments: Guatemala, El Salvador and Nicaragua, in terms of geomorphology and structure (Figure 1). The focal mechanisms (Figure 1b) show how the active deformation in the arc is mainly strike-slip, while in the western part of the Chortis block it is almost pure normal dip-slip. The boundary between the North American and Caribbean plates is clearly seen as a left-lateral shear zone presenting high seismic activity. The subduction zone presents very high activity, dominated by the presence of reverse faulting at the interface between the Cocos and the forearc sliver, and normal faulting associated to the bending and internal deformation of the subducted Cocos plate.

[5] The Cocos plate moves toward the Caribbean plate with a velocity of 70–85 mm/a, with little obliquity [*DeMets*, 2001]. According to *DeMets* [2001] the obliquity is sufficient to lead to partitioning of the subduction slip vector and the formation of strike-slip faults parallel to the trench. The Caribbean plate is moving toward the east taking the North American plate as fixed with 18–20 mm/a [*DeMets et al.*, 2000], as confirmed by recent GPS studies in northern Central America [*Lyon-Caen et al.*, 2006]. To this general setting we must add the 5–10 mm/a of east-west extension taking place in the region of the Honduras grabens [*Cáceres et al.*, 2005; *Guzmán-Speziale*, 2001; *Lyon-Caen et al.*, 2006] which extends approximately from the Ipala graben to the Honduras depression. In Figure 1c are shown the relative motion vectors between the Caribbean, Cocos and North American plates and also the motion of the forearc sliver. These calculations have been done from the poles and data of *DeMets* [2001] and show how the forearc sliver is practically fixed to the North American plate, as confirmed by the local GPS results of *Lyon-Caen et al.* [2006]. This could explain why there are no deformations in southern Mexico if we accept the possible northwestward motion of the forearc sliver in case of effective slip-partitioning. The main goal of this work is to assess how important the various forces involved in the deformation of this area are and how we can reconcile the mentioned differences in the volcanic arc.

3. Model

[6] The presented numerical model is based on the conceptual models of *Burkart and Self* [1985], *Malfait and Dinkelman* [1972] and *Plafker* [1976]. We studied the interaction of three main lithospheric blocks: North American plate, Chortis block and Middle America trench forearc (Figure 2). The limits between these blocks are: Motagua-Polochic-Swan Island fault zone (North American-Caribbean plates boundary) and the Central America volcanic arc weak zone (Chortis block-Forearc sliver boundary). The former is modeled as a free-slip dislocation, which is reasonable for a very well defined boundary with homogeneous behavior through several seismic cycles [*Beekman et al.*, 2000; *Bertoluzza and Perotti*, 1997; *Hubert-Ferrari et al.*, 2003; *Lesne et al.*, 1998; *Lundgren and Russo*, 1996; *Malservisi et al.*, 2003]. The volcanic arc is modeled as a weak zone [*Guzmán-Speziale et al.*, 2005; *Plafker*, 1976]. In the arc the deformation is taking place by means of different families of planes [*Ambraseys and Adams*, 2001; *Carr and Stoiber*, 1977; *Grases*, 1994; *White and Harlow*, 1993] and the rheology is controlled by the presence of the magmatic activity, including different thermal conditions. This approximation has also been taken to model other broad deformation areas [*Meijer and Wortel*, 1996; *Pauselli and Federico*, 2003].

[7] We used the commercial package ANSYS® (ANSYS Inc.). The model consists of 20.238 elastic thin-shell triangular elements with a mean side length of 25 km, which comprises 10.432 nodes, with 100 km of thickness as reference for the calculus (Figures 2b and 2c). The elastic parameters used are 7×10^{10} N m^{-2} for the Young's modulus and 0.25 for the Poisson's ratio. These values are representative of the mean rheology of the lithosphere [*Bertoluzza and Perotti*, 1997; *Kurz et al.*, 2003; *Lesne et al.*, 1998; *ten Veen and Meijer*, 1998; *Wortel and Cloetingh*, 1981]. For the weak zone of the volcanic arc we have tested three values: 7×10^7 N m^{-2}, 7×10^9 N m^{-2} and 7×10^{10} N m^{-2}. The latter value implies there is no weak zone present. The value of 7×10^9 N m^{-2} is used as default in the majority of the models.

Figure 1. Tectonic setting of northern Central America. (a) Tectonic sketch of northern Central America with main structures and interpretations compiled from literature cited in the text. The arrows show relative displacements. The abbreviations are: PF, Polochic fault; MF, Motagua fault; SIT, Swan Island transform; SG, Sula graben; IG, Ipala graben; HD, Honduras depression; GF, Guayape fault; ND, Nicaraguan depression; HE, Hess escarpment. (b) Triangles show the location of quaternary volcanoes. Focal mechanisms are from Harvard CMT catalogue (http://www.globalcmt.org/CMTsearch.html) actualized to 20 March 2007. Plate motion vectors calculated from *DeMets* [2001], taking North America as fixed, with the plate motion calculator of Utrecht University (http://www.geo.uu.nl/~wwwtekto/PlateMotion/), velocities are in mm/a. (c) Forearc sliver (FS) velocity has been recalculated for the new plate reference analogously to *DeMets* [2001] as shown in Figure 1c. The extension rate of the Chortis block has been taken from *Guzmán-Speziale* [2001] and *Lyon-Caen et al.* [2006]. (c) Velocity space construction for the relative movements between Cocos plate (CO), Caribbean plate (CA), North American plate (NA), and the Forearc sliver (FS) for a point situated near the coast of El Salvador (13°N, 89°W). Solid lines are velocities calculated directly from the poles shown by *DeMets* [2001], and dashed lines are velocities calculated graphically assuming 10° of deviation of the mean slip direction at the trench from the plate convergence direction [*DeMets*, 2001].

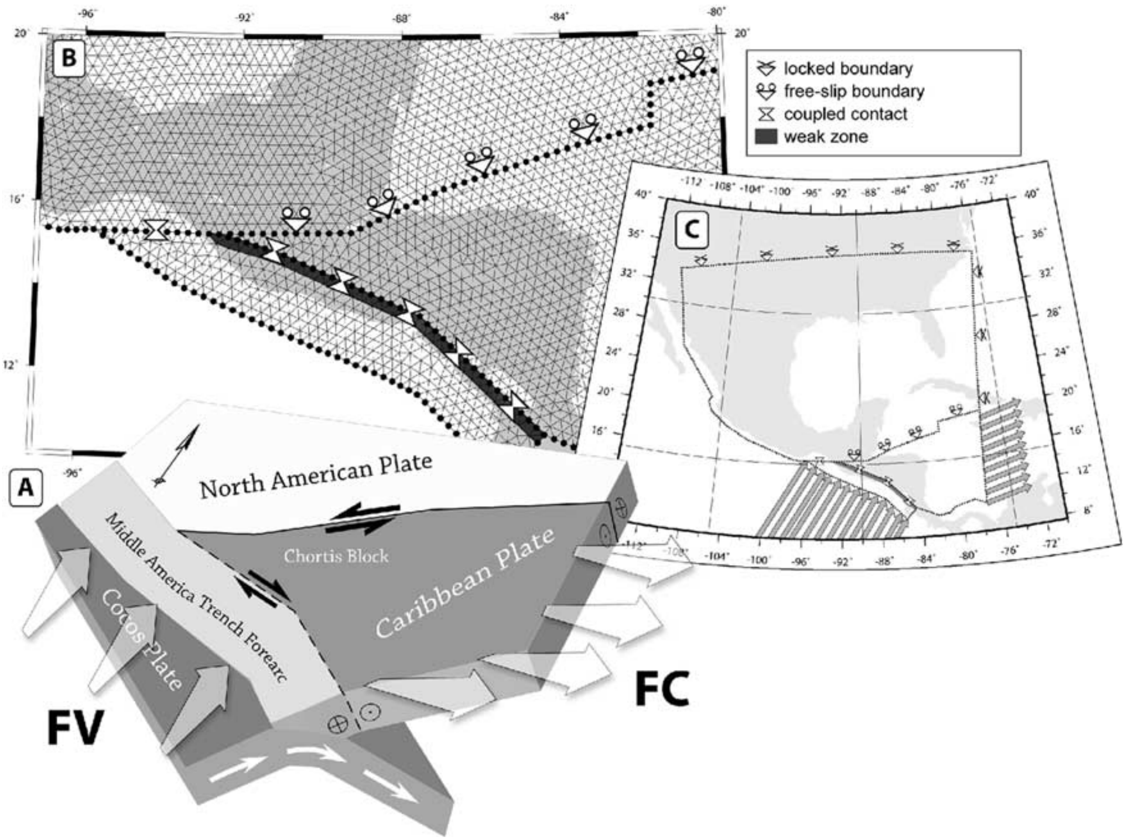

Figure 2. (a) Conceptual sketch of the set up of the numerical model. Abbreviations: FV, trench force vector; FC, Caribbean drift forces (relative to a fixed North American plate). (b) Detail of the mesh used in the area of interest. The meaning of the signs is as shown in the box. (c) Full spatial extent and boundaries of the model.

[8] We have taken into account two main sources of forces: subduction-related forces and Caribbean drift-related forces. Both have been parameterized taking the motion vector from *DeMets* [2001] and have been normalized to a maximum value of 1×10^{12} Nm [*Dyksterhuis et al.*, 2005; *Govers and Meijer*, 2001; *ten Veen and Meijer*, 1998]. We tested the influence of the slip-partitioning at the trench as proposed by some authors [*DeMets*, 2001; *Harlow and White*, 1985] by decomposing the trench force vector into trench-normal and trench-parallel components (Figure 3), and varying the former independently. As we are interested in the stress and strain on the volcanic arc and the Chortis block, we assume that in case of total slip-partitioning the trench-normal component of the force is totally absorbed in the subduction process and as internal deformation in the closest part of the forearc (by means of the reverse fault earthquakes). In this case the trench-normal force applied at the trench in the model is $Fn = 0 \times FN$. We also tested the absence of slip-partitioning by varying both components in the same way, effectively testing the degree of coupling between the plates in the subduction (see Table 1).

[9] The northeastern extension of the Chortis block is welded to the Caribbean plate [*Heubeck and Mann*, 1991; *Malfait and Dinkelman*, 1972; *Meschede and Frisch*, 1998; *Plafker*, 1976] and is moving coherently with it. As we are taking the North American plate as fixed, this motion must exert some influence on the western part of the Chortis block. The direction of this motion has been parameterized and applied as forces with different values in order to test its relative influence in comparison with the trench forces (Table 1). It seems clear from observation that the Chortis block is undergoing extension on its western edge [*Cáceres et al.*, 2005; *Guzmán-Speziale*, 2001; *Malfait and Dinkelman*, 1972; *Mann and Burke*, 1984; *Muehlberger and Ritchie*, 1975] and different hypotheses have been proposed [*Burkart*, 1983; *Burkart and Self*, 1985; *Gordon and Muehlberger*, 1994; *Guzmán-Speziale et al.*, 1989; *Heubeck and Mann*, 1991; *Malfait and Dinkelman*, 1972; *Plafker*, 1976; *Manton*, 1987]. The seismicity shows an absence of significant active deformation to the east of the Honduras Depression, but most clearly, to the east of the Guayape fault toward the Hess escarpment (Figure 1b).

4. Results

[10] We have done 18 different experiments to test (1) the influence of the forces and their relative importance and (2) the degree of weakness of the volcanic arc (Table 1). The models have been named following their main characteristics. There are three groups of models.

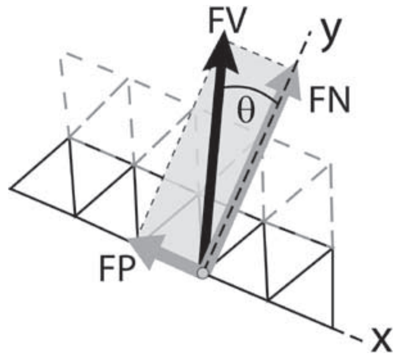

Figure 3. Trench force vector (FV) decomposed into trench-parallel (FP) and trench-normal (FN) forces. Here θ is the angle between the motion vector and the normal to the trench calculated at each node.

[11] 1. The first group comprises models to test the influence of the forces with slip-partitioning at the trench. The first letter refers to the applied trench-normal force, Fn (A, Fn = 1 × FN; B, Fn = 0.6 × FN; C, Fn = 0.3 × FN and D, Fn = 0 × FN), while the second letter refers to the applied Caribbean drift force, Fc (a, Fc = 1 × FC; b, Fc = 0.5 × FC and c, Fc = 0 × FC). The weakness of the arc remains constant.

[12] 2. The second group comprises models to test the degree of weakness of the volcanic arc (M0: no weakness; M1: standard weakness; M2: high weakness) maintaining the forces constant.

[13] 3. The third group comprises models to test the degree of coupling of the subduction zone without slip-partitioning. The trench-normal and trench-parallel forces are varied together and proportionally (T1, Fv = 1 × FV; T2, Fv = 0.6 × FV and T3, Fv = 0.3 × FV) while weakness and Caribbean drift force remain constant.

[14] We present synthetic focal mechanisms for selected earthquakes (Figure 4) and maps of strain crosses and tectonic regime, the latter being defined by the stress ratio, SR (Figure 5),

$$SR = \frac{\sigma_h}{\sigma_H - \sigma_h},$$

where $\sigma_H > \sigma_h$, being the maximum and minimum horizontal stresses respectively. This relation is similar to that of *Angelier* [1979],

$$\Phi = \frac{\sigma_2 - \sigma_3}{\sigma_1 - \sigma_3},$$

where $\sigma_1 > \sigma_2 > \sigma_3$, but working only with the maximum and minimum stresses in order to study the spatial distribution of the tectonic regime. The vertical stress in our models is always zero because there are no restrictions to the vertical strain. Depending on the values of SR we can define the following tectonic regimes: (1) biaxial tension, $SR < -1$; (2) pure uniaxial tension, $SR = -1$; (3) transtension, $-1 < SR < -0.5$; (4) pure strike-slip, $SR = -0.5$; (5) transpression, $-0.5 < SR < 0$; (6) pure uniaxial compression, $SR = 0$; and (7) biaxial compression, $SR > 0$.

4.1. Synthetic Focal Mechanisms

[15] We have followed the methodology of *Meijer* [1995] to calculate the synthetic focal mechanism for a given plane from the state of stress obtained. In Figure 4 we present the focal mechanism and the angular deviation of the calculated slip vector within the selected plane in our synthetic focal mechanism from that of the Harvard CMT database. The observed focal mechanisms are representative of the deformation taking place at the considered segments of the volcanic arc and the Chortis block (Figure 1b). For Honduras the focal mechanism selected is that of the earthquake of 29 September 1982. The nodal plane selected for the calculations is the one striking NNE-SSW and dipping to the west. The focal mechanism of El Salvador is that of the destructive earthquake of 13 February 2001, and the almost vertical E-W plane. The selected Nicaraguan earthquake is the 6 July 2000, and the plane is the NE-SW striking one. As can be seen on Figure 1b, the Harvard CMT catalogue lacks of focal mechanisms in the arc of Guatemala clearly related to the trench-parallel structures. We decided to omit this part of the arc in the synthetic focal mechanism calculus to avoid misinterpretations.

4.1.1. Synthetic Focal Mechanism of the Chortis Block

[16] The state of stress in this area depends mainly on two factors: the drift direction of the Caribbean plate and the small influence of the subduction forces. The models with better approximation to the focal mechanism are Ca, Cb, Cc, Da, Db, M1, T2 and T3. In almost all of them Fn < Fc,

Table 1. Forces Applied in Each Model[a]

Model	Fn	Fp	Fc	E(arc)[b]
Aa	1 × FN	1 × FP	1 × FC	7.0E+09
Ab	1 × FN	1 × FP	0.5 × FC	7.0E+09
Ac	1 × FN	1 × FP	0 × FC	7.0E+09
Ba	0.6 × FN	1 × FP	1 × FC	7.0E+09
Bb	0.6 × FN	1 × FP	0.5 × FC	7.0E+09
Bc	0.6 × FN	1 × FP	0 × FC	7.0E+09
Ca	0.3 × FN	1 × FP	1 × FC	7.0E+09
Cb	0.3 × FN	1 × FP	0.5 × FC	7.0E+09
Cc	0.3 × FN	1 × FP	0 × FC	7.0E+09
Da	0 × FN	1 × FP	1 × FC	7.0E+09
Db	0 × FN	1 × FP	0.5 × FC	7.0E+09
Dc	0 × FN	1 × FP	0 × FC	7.0E+09
M0	0.3 × FN	1 × FP	0.5 × FC	7.0E+10
M1	0.3 × FN	1 × FP	0.5 × FC	7.0E+09
M2	0.3 × FN	1 × FP	0.5 × FC	7.0E+07
T1	1 × FN	1 × FP	0.5 × FC	7.0E+09
T2	0.6 × FN	0.6 × FP	0.5 × FC	7.0E+09
T3	0.3 × FN	0.3 × FP	0.5 × FC	7.0E+09

[a]Fn, applied trench-normal force; FN, total trench-normal force from the original vector (FV); Fp, applied trench-parallel force; FP, total trench-parallel force from the original vector (FV); Fc, applied Caribbean drift force; FC, total Caribbean drift force; and E(arc), Young modulus used in the weak zone of the volcanic arc, in N m^{-2}.

[b]Read 7.0E+09 as 7.0×10^9.

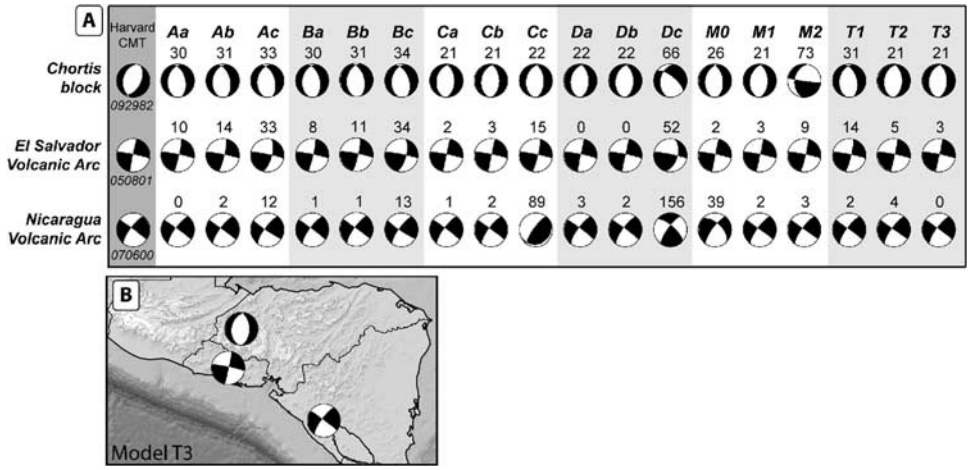

Figure 4. (a) Original and synthetic focal mechanisms for the Chortis block, El Salvador, volcanic arc and Nicaraguan volcanic arc for each model. The number over the "beach balls" is the deviation in degrees from the original rake of the focal mechanism. (b) Calculated synthetic focal mechanisms for the model T3 on their respective areas.

or Fv $\leq$ Fc in case of no slip-partitioning (Fn: applied trench-normal force; Fc: applied Caribbean drift-related force; Fv: applied trench force without slip-partitioning; Table 1). The degree of weakness in the volcanic arc is important to the state of stress of the Chortis block. The model M2 has an excess of weakness and the deviation from the actual focal mechanism is great. The model without weakness (M0) gives a good result but the model M1 (with a Young modulus 1 order of magnitude lower than the rest of the model) gives the best result. Thus incorporating the weak zone which partially decouples the forearc sliver from the Chortis block leads to a better fit with the observations.

4.1.2. Synthetic Focal Mechanism of El Salvador

[17] The deviations from the control focal mechanism are not too large in general, but the greater errors are given by those models without tensional forces due to the drift of the Caribbean plate (Table 1: Ac, Bc, Cc, Dc). The state of stress in the Chortis block, and then the presence of E-W tensional forces, has direct implication on the state of stress on the volcanic arc. When the trench forces are small the results improve noticeably. The models Ca, Cb, M0, M1, and T3 give very good results, but the models Da and Db fit perfectly. These models are characterized by the total slip-partitioning of the forces on the trench, without transmission of trench-normal forces and with relative large Caribbean-drift related forces.

4.1.3. Synthetic Focal Mechanism of Nicaragua

[18] The results for this focal mechanism confirm the necessity of inclusion of tensional forces associated to the Caribbean drift. Independently of the subduction forces the results fit quite well. This small sensitivity can be explained by two factors: on the one hand the almost vertical strike-slip faults tend to generate easily almost horizontal rakes, and on the other hand the strike of the selected planes (NE-SW) is optimally oriented for the direction of the trench forces but also for the direction of the Caribbean-drift forces.

4.2. Stress Shape Factor Maps and Strain Crosses

[19] The stress shape factor maps allow us to study the spatial distribution of the different tectonic regimes and how they depend on the geometry of the blocks and the applied forces. The plotted strain crosses have been selected from the 20.238 elements of the model to show the strain of the areas of interest (Figure 5) and are helpful to compare our results with those of the recent works of *Cáceres et al.* [2005] and *Guzmán-Speziale et al.* [2005]. These authors computed the strain crosses from the Harvard-CMT catalogue. The results of *Guzmán-Speziale et al.* [2005] show an E-W orientation of the extension in the volcanic arc, while in the area of grabens of the Chortis block it forms a 109° angle with the north. In the work of *Cáceres et al.* [2005] the uniaxial extension in the grabens forms an angle of 97°, while in the volcanic arc of Guatemala and Nicaragua the angle is 60° and 66° respectively.

[20] In all our models the state of stress at the volcanic arc is more compressive than in the Chortis block, being mainly transpressive in great part of the models and generally more compressive in Guatemala. Here the stress regime is mainly transpressive independently of the amount of forces transmitted from the trench. In Nicaragua, the models without Caribbean drift forces show transpression, but with drift forces being more important than the trench forces the stress regime is mainly transtensive (models Ca, Da and Db). In El Salvador the stress regime is transpressive in the models with high trench-normal forces (models A and B), but transtensive with low trench-normal forces (models C and D). In the latter models another interesting feature appears: a zone of pure extension in a broad band from the Sula graben, at the North America-Caribbean boundary, to the Gulf of Fonseca, with NNW-SSE direction.

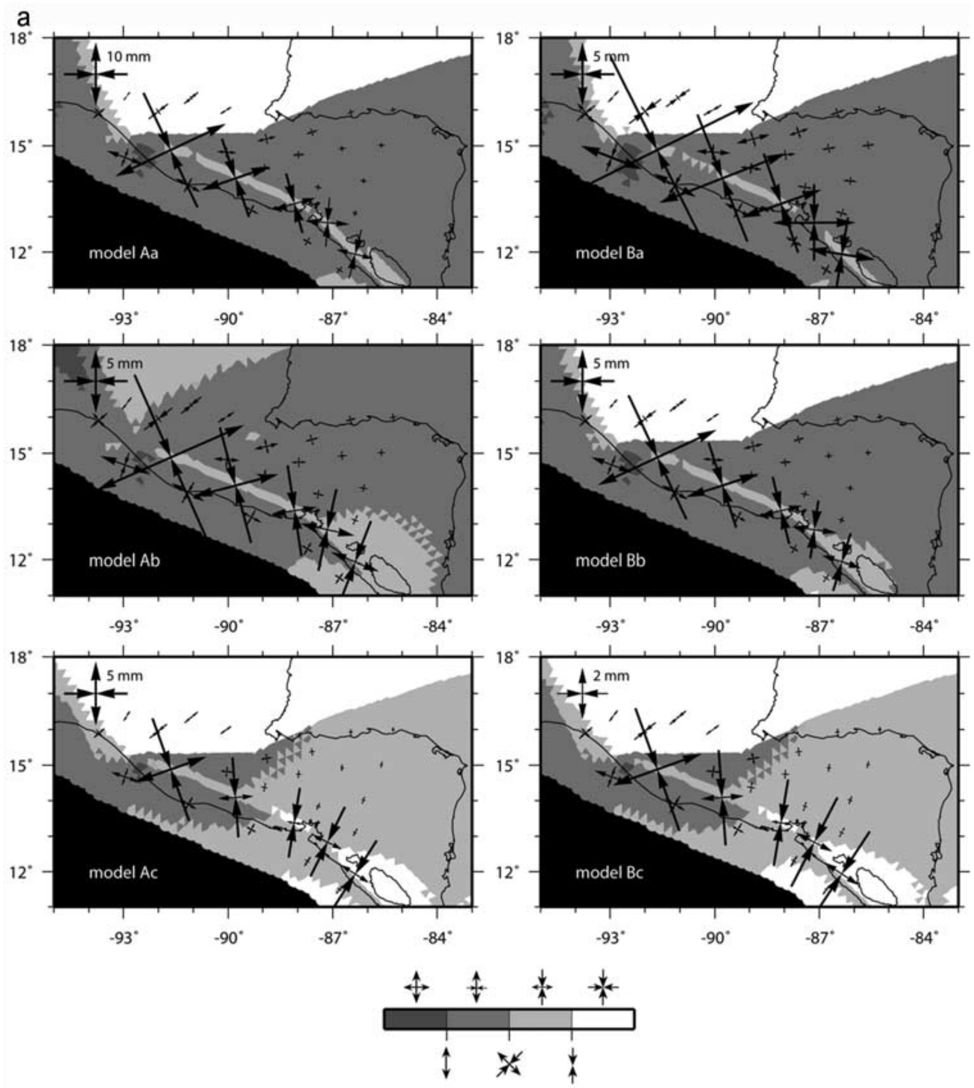

Figure 5. Maps of tectonic regime (from the SR value) and strain crosses. The grey shading is coded as a function of the kind of tectonic regime as is shown in the scale bar. Note that the scale of the strain crosses, at the top left in each map, varies from one model to another. The value of strain is expressed in millimeters for scale convenience. The amount of strain is proportional to the volume (and thus to the reference thickness of the shell). The values have no direct physical meaning and are just shown for comparison.

[21] Another general feature is the orientation of the strain crosses. At Nicaragua, the lower the force of the Caribbean drift, the higher the azimuth of the tensional vector. Tension rotates from E-W to SE-NW, near the Gulf of Fonseca. At Guatemala and El Salvador the orientation remains approximately constant. The relation between the compression and tension in the strain crosses is proportional, obviously, to the relation of the applied forces. In the Chortis block the direction of extension is always approximately E-W, but the extensional regime is only achieved when the trench forces are small (compare Figures 5a and 5b).

[22] The influence of the degree of weakness of the volcanic arc is noticeable only in the amount of deformation (Figure 5c). The weaker the arc, the greater the deformation on it, in relation to the deformation of the Chortis block. If there is no weakness in the arc, the deformation at the Chortis block is greater than in the arc. In contrast, if the weakness is too high (case M2) the deformation in the Chortis block is negligible. One order of magnitude of difference in the Young's modulus shows differences in the strain of around 2–10 times greater on the arc depending on the relation of forces.

5. Discussion

[23] The models that best fit the calculated strain [*Cáceres et al.*, 2005; *Guzmán-Speziale et al.*, 2005], seismicity, and geological observations are the Ca, Da, Db

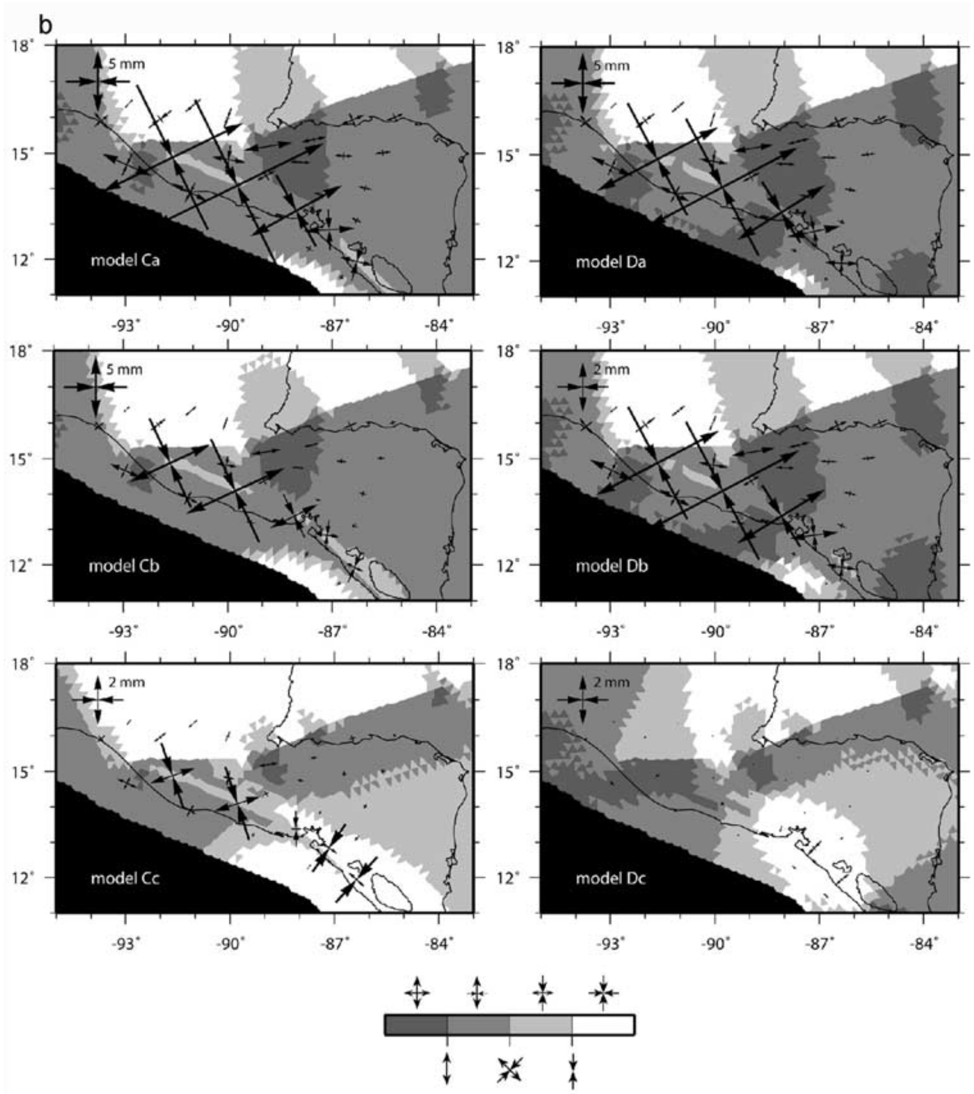

Figure 5. (continued)

and T3. These models have the following common characteristics: small or null magnitude of the trench normal forces, a degree of weakness of the volcanic arc 1 order of magnitude lower than the rest of the model and a medium to high magnitude of the Caribbean drift forces. The existence of slip-partitioning at the trench is not key to the state of stress on the volcanic arc. In the following discussion we will refer to these models exclusively (the aforementioned models: Ca, Da, Db and T3). It is important to have in mind that this model is a first-order approximation and that some different constraints and forces could be taken into account to refine it (for example, mantle up welling related forces [*Rogers et al.*, 2002]) or trench retreat forces associated to a hypothetic rollback of the Cocos plate). Nevertheless the results are good enough to form a solid base to discuss some characteristics of the geodynamic setting of northern Central America. In the Chortis block the predominant stress regime is the transtensional, with a broad zone of pure extensional deformation from the Sula graben toward the Gulf of Fonseca. These results match well with the observations. The focal mechanisms that are reported in the area are normal, or normal-oblique (Figure 1b). The strain crosses calculated in the zone [*Cáceres et al.*, 2005; *Guzmán-Speziale et al.*, 2005] are identical to the strain crosses of our models.

[24] The structure in the area presents a series of grabens displaced by strike-slip faults [*Mann and Burke*, 1984; *Manton*, 1987] and a corridor that makes up the Honduras depression from the Sula graben to the Gulf of Fonseca [*Mills et al.*, 1967; *Muehlberger*, 1976], which could be explained by our results. The volcanic arc presents mainly strike-slip deformation with transtension or transpression depending on the segment. The arc in Guatemala presents always transpression in our models; the reported focal mechanisms are strike-slip with small vertical component, although the elevation of the arc is very high compared with

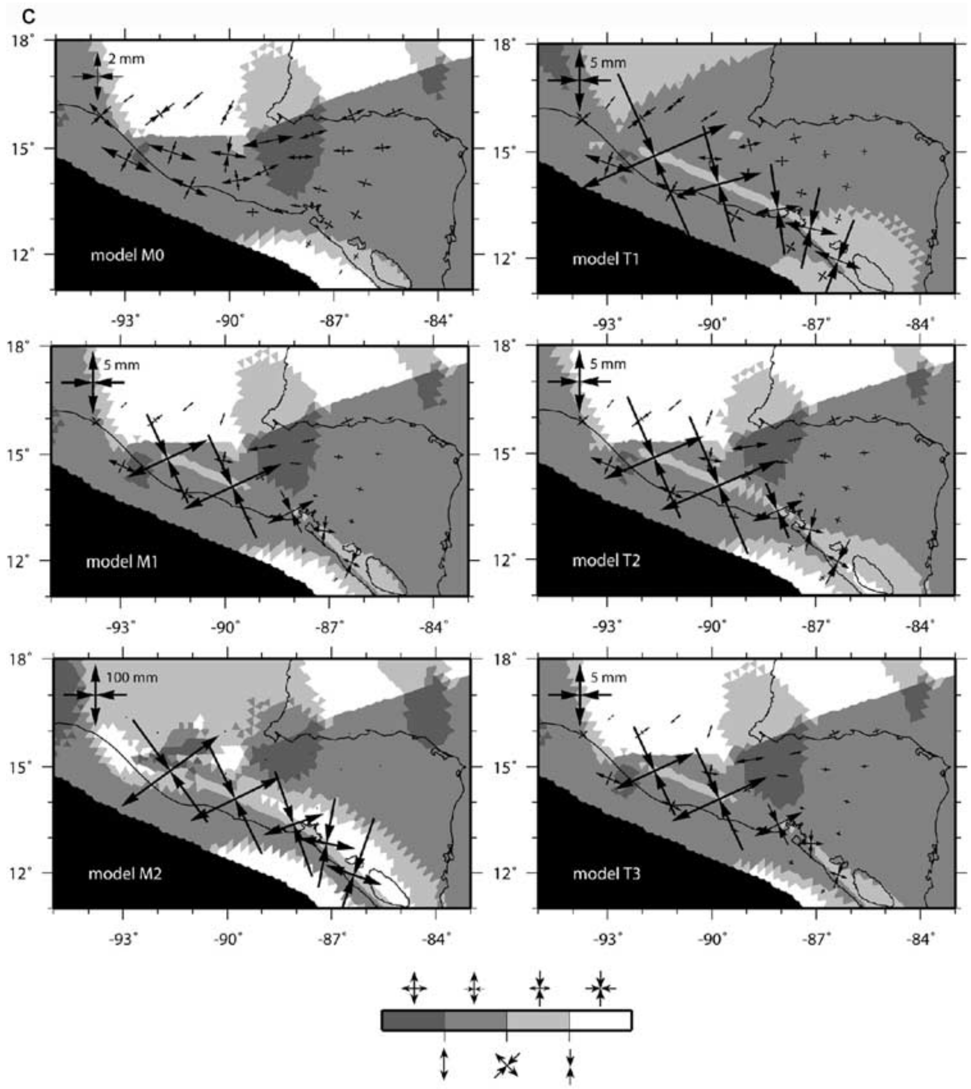

Figure 5. (continued)

the rest of the arc, resembling an Andean type cordillera. This elevation probably depends on processes taking place in the overriding plate and not on the subduction interface. A possible cause could be the absorption of the main part of the extensional deformation of the Chortis block in the area toward the southeast of the bending of the Motagua fault. This limit approximately coincides with the presence of the Ipala graben and the transition from the arc of Guatemala to the arc of El Salvador. Therefore the arc in Guatemala experiences in less degree the effect of the drifting of the Caribbean plate. Moreover, if there is some slip-partitioning at the trench, this part of the arc must accommodate a fraction of the relative motion of the forearc sliver toward the northwest, pushed against the North American plate on its northern edge.

[25] The arc in the segments of El Salvador and Nicaragua shows mainly transtensional deformation, although the Nicaraguan part shows some transpression too. The focal mechanisms reported in these zones are pure strike-slip (Figure 1b), although there are geological data supporting the existence of transtensional structures in El Salvador [*Carr*, 1976; *Corti et al.*, 2005] and in Nicaragua, as is evidenced by the low topography and the presence of the partially inherited Nicaraguan Depression [*Cowan et al.*, 2002; *La Femina et al.*, 2002; *Weinberg*, 1992]. The arc in Nicaragua should experience more extension than in our models in view of the geology. This disagreement must be due to our simplification of the boundary conditions in this part. On the one hand the influence of the compressive structures in the southern part of the volcanic arc (Costa Rica, Panama) has not been taken into account and on the other hand the subduction process could have features in this area that escape our model. The former is due to the north-northeastward vergence of the compressive structures, which are not expected to transmit a significant amount of stresses toward the northwest. Nevertheless, the overall

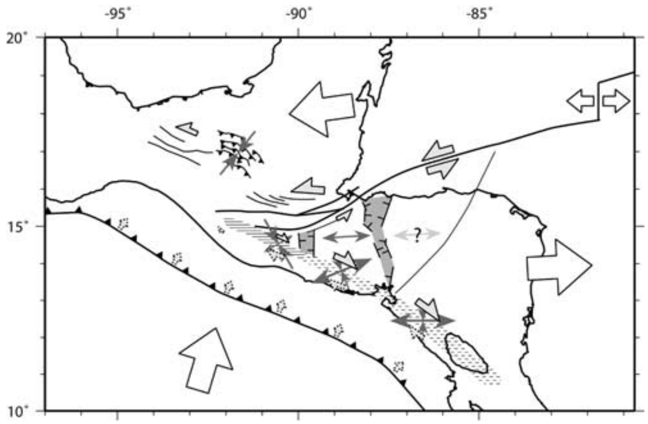

Figure 6. Sketch of the discussed tectonic model for the northern of Central America. Large white arrows show the main tectonic forces acting over the Western Chortis block. Light grey outlined arrows show relative motions on faults. The dashed arrows show the relative motion of the forearc sliver in case of effective transmission of forces by means of a low coupled subduction zone. Dark grey arrows show idealized strain crosses. Grey shaded areas represent the main extensional features in the Chortis block decoupling the Caribbean plate from the North American plate: the Ipala graben and the Honduras depression. Solid horizontally ruled area is the volcanic arc of Guatemala, showing transpressive tectonic regime. Dashed horizontally ruled area is the volcanic arc in El Salvador and Nicaragua, showing transtensional tectonic regime. Hachured lines mark the approximated limits of the Ipala graben and the Honduras depression. Solid lines are some of the main strike-slip structures. Lines with triangles mark main compressional structures.

results are in good agreement with the observations and we are confident in the basis of our inferences.

[26] The orientation of the strain crosses at the volcanic arc in our model fits quite well the strain calculated by *Cáceres et al.* [2005], except for Nicaragua, where there is a clockwise deviation of 30°. The strain cross calculated by *Guzmán-Speziale et al.* [2005] comprises the entire volcanic arc, for that reason it is more limited and only comparable to our distributed strain crosses in a qualitative way. The tensional axis of our strain crosses are generally more NE-SW directed than the E-W direction of the cross of *Guzmán-Speziale et al.* [2005], especially in the arc of Guatemala and El Salvador.

6. Conclusions and Implications for the Regional Tectonics

[27] Figure 6 shows a schematic tectonic model compiling some ideas from authors cited in the text and including our conclusions. We have taken the North American plate as fixed for modeling purposes and this is maintained during the tectonic discussion. In fact the fixed one seems to be the Caribbean plate [*Müller et al.*, 1999], and therefore the extensional forces are related to the drift of the North American plate, nevertheless the results are the same.

[28] The state of stress in the area of grabens of the Chortis block is the result of the combination of three factors: the drift direction of the eastern part of the Chortis block toward the east-northeast, the curvature and structure of the North American-Caribbean boundary, and a low to very low degree of coupling of the subduction zone. The state of stress in the volcanic arc depends on the tensional forces due to the drift of the Caribbean plate, the presence of a weakness zone in the volcanic arc, and a low degree of coupling in the subduction, independently of the occurrence of slip-partitioning.

[29] Assumption of a weakness zone in the volcanic arc is necessary to achieve results comparable to the actual observations. This weakness must be less than 1 order of magnitude lower than the surrounding materials. The existence of elevated topography on the volcanic arc in Guatemala could be due to the geometrical characteristics of the boundaries in this area. The subduction forces and the motion of the forearc sliver, even without slip-partitioning as a part of the Chortis block, push the arc against the North American plate, pinning the block and promoting its relative uplift.

[30] From a tectonic point of view, the Middle America subduction zone in northern Central America must exhibit a low or very low degree of coupling [*Lyon-Caen et al.*, 2006; *Pacheco et al.*, 1993]. This can be a consequence of the geometry of the slab and/or the relative motion between the Caribbean and Cocos plates [*Heuret and Lallemand*, 2005; *Scholz and Campos*, 1995; *Uyeda*, 1982]. The occurrence of slip-partitioning at this trench appears not necessary to achieve the actual state of stress in the volcanic arc, although we cannot rule out its presence. If it is happening, the deformation must be accommodated through inherited structures generated mainly by the relative motion of the Chortis block toward the east.

[31] The presence of tensional forces related to the relative eastward drift of the Chortis block, implies the existence of internal deformation on its western edge as a part of the diffuse triple junction. This must be due to the pinning of the arc in the area of Guatemala, partly supporting the hypothesis of *Burkart and Self* [1985] and *Malfait and Dinkelman* [1972] among others.

[32] As is evidenced by the seismicity, the tectonic regime in the volcanic arc is strike-slip, with more important reverse components in the Guatemalan segment. The orientation and magnitude of the strain ellipsoid in the volcanic arc depends on the equilibrium of the subduction and Caribbean drift forces. These results are coherent with those of *Cáceres et al.* [2005] and *Guzmán-Speziale et al.* [2005]. The relative importance of the Caribbean drift associated forces is greater than the importance of the trench forces, owing to the required low coupling of the latter.

[33] The existence of the Honduras depression as a deformation corridor, composed of normal faults between the Gulf of Fonseca and the Sula graben, is a direct consequence of the geometry of the shear zones limiting the Chortis block and the presence of tensional stress. This

fact could explain the compartmentation of the Chortis block proposed by *Burkart* [1983] and the differences between the El Salvador and Nicaraguan segments of the volcanic arc, being part of different blocks [*Cáceres et al.*, 2005].

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