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Reassessment of the Paleogene position of the Chortis block relative to southern Mexico: hierarchical ranking of data and features

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ABSTRACT

The Paleogene location of the Chortis block relative to southern Mexico is presently a hotly debated topic, with various types and qualities of data brought to bear on the topic. There are currently three competing Cenozoic reconstructions: (i) the traditional model that places the Chortis block adjacent to southern Mexico, (ii) the near in situ model in which the Chortis block is located relatively near to its present position, and (iii) the Pacific model that places the Chortis block WSW of its present location. To provide some order to this debate, we rank data into three levels on the basis of reliability and relevance: 1st order plate tectonic features that define the relative motion and amount of displacement of the plates, paleomagnetic data that provide paleolatitudinal constraints, and essential elements for any model; 2nd order piercing points that can be matched in both continental areas, the Chortis block and southern Mexico, and Cenozoic magmatic arcs that can predict plate tectonic scenarios; and 3rd order pre-Cenozoic features. The orientation, size and patterns of the magnetic anomalies in the Cayman Trough have been interpreted in terms of 1100 km of relative sinistral motion between North America and the Caribbean since 49 Ma and favor the Pacific provenance of the Chortis block from a WSW position, however, internal deformation of the Chortis and Maya blocks as well as uncertainties in the identification of old segments of magnetic anomalies suggest that the relative displacement between the Chortis and Maya blocks could be at least 200 km less. The traditional model, although satisfying two 1st order criteria, contravenes another 1st order element, namely the undeformed nature of the Cenozoic sediments in the Gulf of Tehuantepec, which requires a re-evaluation of the model. The interpretation of a Paleogene intra-Pacific position for the Chortis block, southwest of its present position, is more compatible with first order data and resolves some incompatibilities of the traditional model but its viability largely depends on the revision of the total Cenozoic Caribbean plate displacement relative to North America and the Cretaceous trajectory of the Chortis block.

Key words: tectonics, paleogeography, Chortis block, Caribbean plate, southern Mexico.

RESUMEN

La ubicación paleógena del bloque de Chortis con respecto al sur de México es objeto de un intenso debate, en el que se han invocado varios tipos y calidades de datos. Actualmente existen tres reconstrucciones paleogeográficas alternativas: (i) el modelo tradicional que ubica al bloque de Chortis adyacente al sur de México, (ii) el modelo in situ que ubica al bloque de Chortis relativamente cerca de su posición actual, y (iii) el modelo que propone una localización al WSW de su posición actual, en el Océano Pacífico. Con el propósito de dar cierto orden a la discusión, los autores han caracterizado los datos en tres niveles, basados en su certidumbre y su pertinencia: 1er orden, los rasgos y datos que indican el movimiento relativo y la cantidad de desplazamiento de las placas tectónicas, datos paleomagnéticos que proveen restricciones paleolatitudinales, y elementos esenciales para cualquier modelo; 2º orden, los rasgos cenozoicos en las áreas continentales del bloque de Chortis y el sur de México, y arcos *magmáticos cenozoicos que pueden predecir escenarios de tectónica de placas; y 3er orden, los rasgos precenozoicos. La orientación, tamaño y el patrón de anomalías magnéticas de la fosa del Cayman han sido interpretados como al menos 1100 km de desplazamiento izquierdo relativo entre Norteamérica y el Caribe desde 49 Ma y favorecen una procedencia del bloque de Chortis desde una posición al WSW de su posición actual, sin embargo, la deformación interna de los bloques Chortis y Maya, así como la incertidumbre en la identificación en los segmentos antiguos de las anomalías magnéticas sugieren que el desplazamiento relativo entre el bloque de Chortis y el bloque Maya pudo haber sido por lo menos 200 km menor. Aunque el modelo tradicional satisface dos de los criterios de primer orden, contraviene otro elemento de primer orden, representado por la naturaleza no deformada de los sedimentos cenozoicos del Golfo de Tehuantepec, lo cual requiere de una reevaluación del modelo. La interpretación de una posición intrapacífica para el bloque de Chortís en el Paleógeno, al suroeste de su posición actual, es más compatible con datos de primer orden y resuelve algunos de los problemas que plantea el modelo tradicional, sin embargo, su viabilidad depende de la revisión del desplazamiento cenozoico total de la placa del Caribe con respecto a Norteamérica y de la trayectoria cretácica del bloque de Chortis.*

Palabras clave: paleogeografía, tectonica, bloque de Chortis, placa del Caribe, sur de México.

INTRODUCTION

The Paleogene and subsequent paleogeographic locations of the Chortis block are currently a matter of debate. Tectonic features in the Caribbean and southern Mexico display a complex scenario that has led to diverse interpretations (Figure 1). Alternative paleogeographic models depend on the type of data used, varying from plate tectonics of the Caribbean plate to geologic features in southern Mexico and the Chortis block. The allochthonous character of the Chortis block is clear in Jurassic Pangean reconstructions because northern South America lies in the space now occupied by the Chortis and Maya blocks, which are moved westwards and northwards, respectively (*e.g.*, Pindell and Dewey, 1982; Ross and Scotese, 1988; Dickinson and Lawton, 2001; Keppie, 2004; Pindell *et al*. 2006; Giunta *et al*., 2006). Separation of North and South America during the Mesozoic is inferred to have stranded the Chortis block on the North America-Mexican margin. However, the timing and trajectory of relative displacement of the Chortis block to its present-day position largely depend on the weight given to types of data used. The plethora of models may be grouped into three categories: (i) the *traditional* model places the Chortis block adjacent to southwestern Mexico between 95ºW and 105ºW, with migration occurring throughout the Cenozoic (*e.g.*, Pindell *et al*., 2006, and references therein: Rogers *et al*., 2007a); (ii) the *in situ* model infers little or no relative motion, the Caribbean Plate forming in place during the separation of North and South America (*e.g.*, Meschede and Frisch, 1998; James, 2006); and (iii) the *Pacific* model locates the Chortis block WSW of its present position rotating it throughout the Cenozoic (Keppie and Morán-Zenteno, 2005) (Figure 2). In order to provide an objective method for discussion, we present an hierarchical ranking of available tectonic and geological data, and review the various models in this context. We conclude that first order plate tectonic measurements in the Cayman Trough are compatible with both traditional and Pacific models, however, the intact Cenozoic basin in the Gulf of Tehuantepec requires movement of the Chortis block to have passed farther south.

CURRENT MODELS

Many current models for the evolution of the Caribbean plate and its passenger, the Chortis block, have recently been reviewed (*e.g.*, Pindell *et al*., 2006; James, 2006; Giunta *et al*., 2006; Rogers *et al*., 2007a), to which the reader is referred for a more comprehensive treatment. Thus, only salient points will be fully discussed as they relate the hierarchical ranking proposed below. According to prevalent models of Caribbean evolution, significant tectonic episodes for the northern part of the Caribbean plate include: a) Late Cretaceous introduction of an anomalously thick segment of Farallon oceanic lithosphere into the gap between North and South America from a Pacific location; b) northeastward migration of the Caribbean plate and subsequent collision of the leading edge with the Bahamas platform in Eocene time (Iturralde-Vinent, 1994); and c) early Eocene relocation and reorientation of the boundary between the Caribbean and North American plates from Yucatan-Cuba to the Cayman Trough, at which time the Chortis block was transferred to the Caribbean plate (*e.g.*, Pindell and Dewey, 1982; Pindell *et al*., 1988, 2006; Ross and Scotese, 1988; Pindell and Barrett, 1990; Leroy *et al*., 2000) (Figure 3).

HIERARCHY OF FEATURES AND DATA

Paleogeographic reconstructions involve the organization, processing and evaluation of a number of data and features that make this task a complex exercise. The degree of certainty of specific interpretations depends not only on the reliability of the observations and data, but also on the general coherence and simplicity of the proposed model.

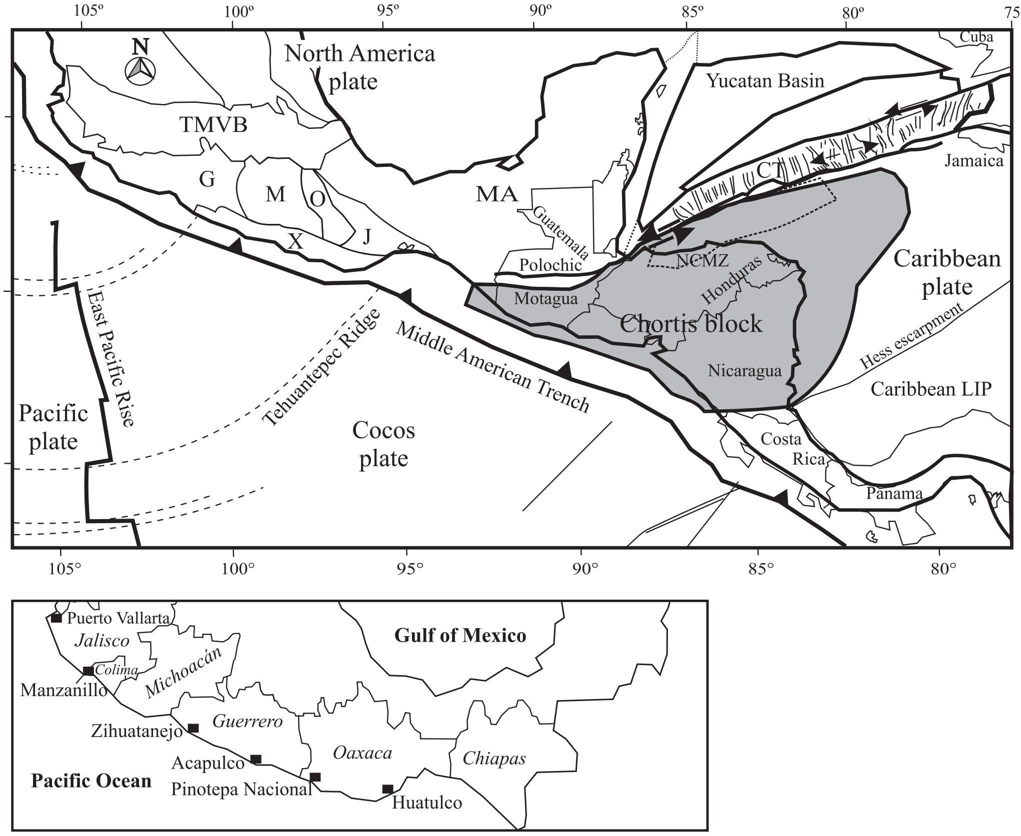

Figure 1. Present-day tectonic scenario of the Caribbean region modified from Rogers *et al*. (2007a). For reference, the political divisions of the southwestern margin of Mexico are indicated in the lower frame. Tectonostratigraphic terranes of southern Mexico after Campa and Coney (1983): G: Guerrero, M: Mixteca, O: Oaxaca, X: Xolapa, MA: Maya, J: Juarez, NCMZ: Northern Chortis metamorphic zone, CT: Cayman Trough, TMVB: Trans Mexican Volcanic Belt.

Any specific observation is relevant if it can only be explained by one particular model; if the observation can be explained by various models then its significance decreases. Furthermore, some observations are such that they must be incorporated and will lead to failure of a model if they cannot be accommodated. In the discussion of the possible southern Mexico – Chortis connections certain geological and geophysical data have been invoked in support of specific models. However, these data are of varying quality, reliability and relevance and in some cases open to different interpretations. In order to test different paleogeographic reconstructions for the Chortis block during the Cenozoic, data and observations can be ordered in a hierarchical classification, defining groups with different degrees of pertinence and/or certainty. This classification considers the possible influence of first order data and/or larger features over data from smaller features and/or a lower degree of reliability. Among the main criteria in evaluating the hierarchy of a group are the age of features in relation to the location of the Chortis block at various times during the Cenozoic. In general, the older the feature, the lower the relevance to Cenozoic reconstructions based on well documented Cenozoic features. For instance, given the Triassic and Early Jurassic juxtaposition of North and South America and the later disruption of Pangea, pre-Mesozoic metamorphic basement affinities allow several different possibilities. Other important criteria are the number and reliability of certain groups of data and the degree of compatibility among them. Based on these statements, the specific classification for reconstructions of the Chortis block location during the Cenozoic is as follows:

First order

a) Quantitative plate tectonic features that define the age, orientation, kinematics and rates of displacement along plate boundaries

Calibration of magnetic anomalies and orientation of associated offsets in the Cayman Trough system may be classed as first order. Based upon the identification of magnetic anomalies and bathymetric data in the Cayman Trough, a pull-apart basin between offset segments of a transform fault, Rosencrantz and Sclater (1986), Rosencrantz *et al.* (1988), and Leroy *et al*. (2000) calculated the age, amount of extension and spreading rates in the Cayman Trough, and the pole of rotation located near Santiago, Chile (Jordan, 1975; Pindell *et al*., 1988). Thus, Rosencrantz and Sclater (1986) and Rosencrantz *et al*. (1988) estimated the total

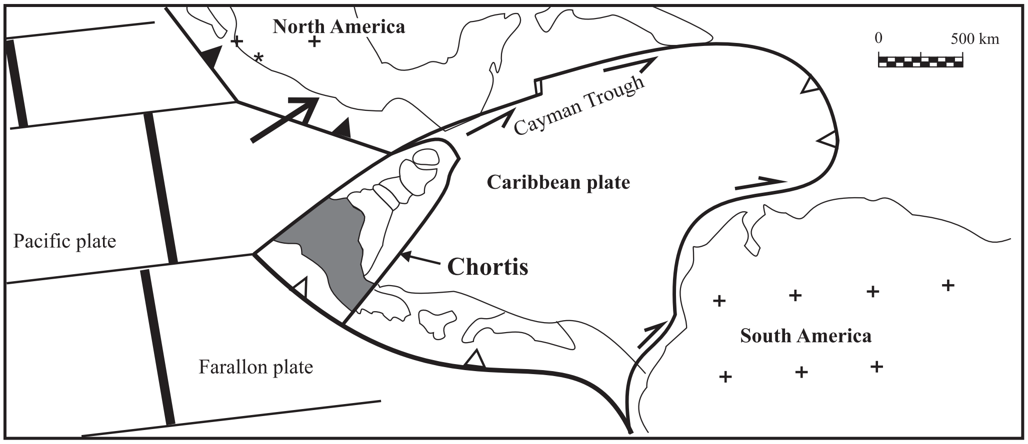

Figure 2. Alternative model for the Paleogene position of the Chortis block proposed by Keppie and Morán Zenteno (2005).

sinistral offset across the Cayman Trough to be *ca.* 1100 km since 44 Ma at a rate of 50 mm/yr between 44 and 30 Ma and 15 ± 5 mm/yr after 30 Ma. Rosencrantz (1993) pointed out that magnetic anomalies of the older stage in the eastern segment of the Trough trend at an angle to magnetic anomalies of the younger stage and rift margin tracers, leading to the suggestion that the older stage anomalies do not fit the dominant reconstructions for the Caribbean plate. More recently, Leroy *et al*. (1996, 2000) calculated a similar, *ca.* 1100 km, sinistral offset and located the continent-ocean transition at the A22 anomaly, which corresponds to an early Eocene age (49 Ma). This allowed Leroy *et al*. (2000) to calculate spreading rates of 17–20 mm/yr over the last 43 Ma, but a slower rate (15 mm/yr) between 43 and 49 Ma. Given the low amplitude of the magnetic anomalies, Leroy *et al*. (2000) expressed uncertainties in the recognition of some anomalies but, in general, their conclusions that the Cayman Trough opened during the Cenozoic are similar to those of Rosencrantz *et al*. (1988), with a slight difference in its initiation: middle versus early Eocene.

Uncertainties in the identification of anomalies older than anomaly 6 (early Miocene) in the Cayman Trough led James (2006) to suggest that most of the pre-Miocene Cayman-Motagua-Polochic offset (900 km) may have occurred during the Jurassic and Early Cretaceous. James (2007) suggested that the Motagua zone, as the western continuation of the Cayman system, is not a suture but a sinistral offset juxtaposing elements (Chortis and Maya blocks) with similar geological history, and concluded that they never were separated by oceanic crust.

However, this is incompatible with dominant interpretations indicating that the northern margin of the Caribbean plate during the Mesozoic lay in Cuba (Iturralde-Vinent, 1994; Leroy *et al*., 2000). Even accepting the uncertainties in the offset timing, it is hard to conceive that continuous lineal morphological features like the Cayman Trough and the Motagua fault could contain a time break in the offset of about 100 Ma. One remarkable feature in evaluating this possible break is the occurrence of the collisional assemblages recognized along the Motagua fault zones (Donnelly *et al*., 1990; Pindell and Barrett, 1990; Harlow *et al*., 2004).

The *ca.* 1100 km estimates of sinistral displacement across the Cayman Trough assume rigid plates, however, interpretation of seismic reflection data indicates that the Maya block was deformed during post-Oligocene times. Thus, Mandujano-Velázquez and Keppie (in press) calculated 106 km of shortening occurred in the Sierra Madre of Chiapas during the Miocene. To the south of the Motagua fault, post-Oligocene extensional deformation has been documented. Based on time extrapolation of GPS-derived plate vectors (DeMets *et al*., 2000), Rogers and Mann (2007) have estimated an E-W extension of 45 km in a 340 km wide zone of rifting in western Honduras and southern Guatemala since 12 Ma. The extension was interpreted by these authors in terms of transtensional tectonics and they suggested that the GPS results obtained by DeMets *et al*. (2000) indicate a present-day coupling across the North America-Caribbean plate boundary in Guatemala. Extension related to older episodes in the northern Chortis block and in the Nicaragua Rise have not been estimated (Ross and Scotese, 1988) but the occurrence of pre-Miocene N-S trending grabens in the former and the attenuated character of the crust in the latter suggest extension during opening of the Cayman (Rogers and Mann, 2007). Thus, we conservatively estimate a total of *ca.* 100 km of E-W tectonic extension in Honduras and the Nicaragua Rise since the Eocene. This, together with shortening in Chiapas, can account for at least 206 km of the 400–600 km offset across the Cayman Trough calculated from the spreading rates in the Cayman Trough in the last 30 Ma (Rosencrantz and Sclater, 1986; Leroy *et al*., 2000). Furthermore, it reduces the offset between the Chortis and Maya blocks by the same amount to 200–400 km (post 30 Ma) and 900 km (post 49 Ma). It has been suggested that the western part of the Chortis-North America plate boundary might be locked at the present time with the interplate strain distributed in zones of reverse faults and strike slip faults of the Chiapas region (Guzmán-Speziale and

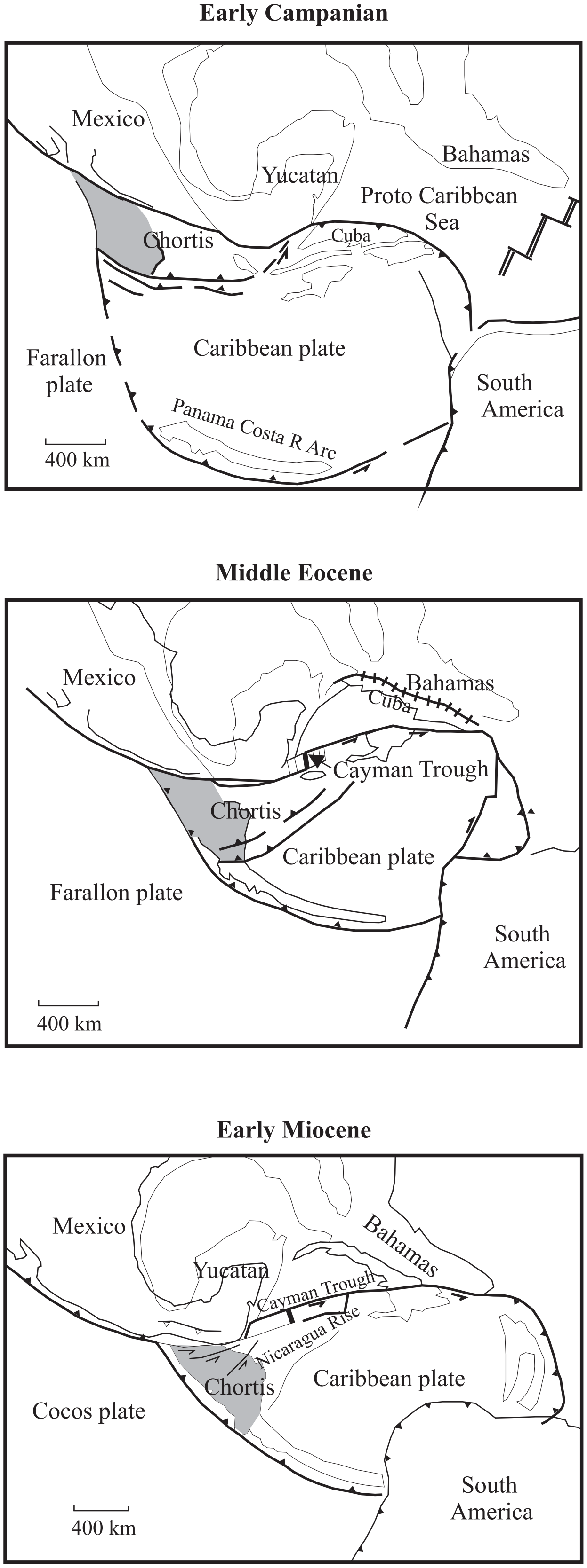

Figure 3. Paleogeography and tectonics of the Caribbean plate, simplified from fig. 4 in Pindell *et al.* (1988) at three different stages: a) Early Campanian, b) Middle Eocene, c) Early Miocene.

Meneses-Rocha, 2000) (Figure 4). On the other hand, the interplate strain seems to be partly accommodated through E-W extension in the northern part of the Chortis block (Guzmán-Speziale, 2001).

In conclusion, we believe that the geophysical data in the Cayman Trough provides overwhelming evidence for the age and direction of sinistral displacement on the northern transform margin of the Caribbean plate that must be accommodated in any model. Between the Chortis and Maya blocks the *ca.* 1100 km of displacement must be adjusted to accommodate the *ca.* 200 km of intraplate deformation. These first order data are only consistent with the traditional and Pacific models, both of which require some modification to allow for intraplate deformation (Figure 5). This figure shows the locations of the western tip of the Chortis block at 30 Ma using different rates of displacement along the Cayman Trough calculated by Rosencrantz and Sclater (1986) and Leroy *et al.* (2000) and the effect of internal deformation in the Chortis and Maya blocks. The reference date of 30 Ma was selected because the last pulses of arc magmatic activity occurred along the continental margin of eastern Guerrero and western Oaxaca at this time. As a starting point for the restorations we used the intersection of the southwesterly projection of the Cayman strike slip structures with the Middle American trench (Figure 5). In this approach, estimations of paleopositions avoid passing the northern boundary of the Chortis block across the intact Chiapas marine platform and the Gulf of Tehuantepec. Figure 5 provides the framework for evaluation of lower order features, such as possible implications in the arc-magmatism extinction patterns and tectonic deformation in southwestern Mexico.

b) Paleomagnetic data can constrain the paleolatitude, but not the paleolongitude, of blocks at times of magnetization within the ±5° minimum error

In the case of the Chortis block, studied sites in Honduras and Nicaragua correspond mainly to rocks ranging in age from 140 to 60 Ma (Gose, 1985). Only the youngest data can be applied to Cenozoic reconstructions, and they suggest that the Chortis block lay at 16°N, *i.e.* one degree north of its present-day latitude relative to North America. Cretaceous paleomagnetic data indicate a similar paleolatitude, but involved a very large clockwise rotation during the Early Cretaceous followed by a counterclockwise rotation in the Late Cretaceous (Gose, 1985). To date only Gose's data have been used to constrain the orientation of the Chortis block, however, the paleolatitudinal data are consistent with all three models: traditional, *in situ* and Pacific.

c) Essential elements to any model are features that must be incorporated for a model to be viable

In the case of the Chortis block reconstructions, an essential element in any reconstruction must account for the tectonically undisturbed, Late Cretaceous-Quaternary section in the Gulf of Tehuantepec and the adjacent

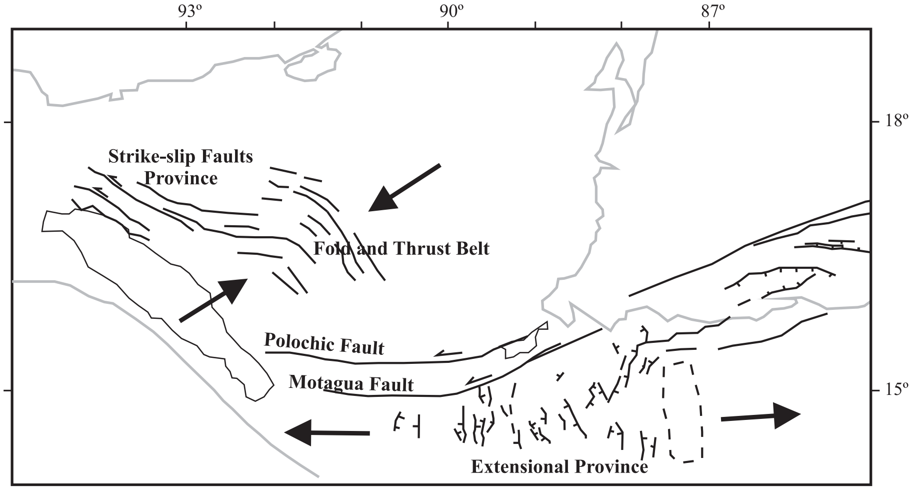

Figure 4. Tectonic features of northwestern Chortis block and southern Mexico on both sides of the Polochic-Motagua system. Integrated from Guzmán-Speziale and Meneses Rocha (2000) and Rogers and Mann (2007). Shortening in the fold and thrust belt was active in the middle Miocene time (Mandujano-Velázquez and Keppie, in press). Extension in the northwestern Chortis block has been documented since at least 12 Ma (Rogers and Mann, 2007).

continental margin (Sánchez-Barreda, 1981) (Figure 6), which shows no features to indicate the Cenozoic passage of the Chortis block along a line connecting the Acapulco trench and the Polochic-Motagua fault system. This observation is compatible with both the *in situ* and Pacific models, however, it cannot be accounted for by the traditional model.

The presence of Cretaceous oceanic elements along the Motagua fault zone is an element that must be incorporated in any Late Cretaceous reconstructions. These oceanic elements include MORB and oceanic island arcs located between the Chortis and Maya blocks that caught in the intervening suture and obducted during the latest Cretaceous-Eocene collision between the blocks (Harlow *et al*., 2004; Giunta *et al*., 2006). The presence of arc magmatism implies that the intervening ocean was at least 100 km wide. However, this element predates the topic of this paper, *i.e.* the Cenozoic models.

Second order

a) Piercing points that can be correlated from southern Mexico to the Chortis block

To date no Cenozoic piercing points have been identified in the Chortis block that can be matched with those in southern Mexico. Keppie and Morán-Zenteno (2005) were unable to identify in the Chortis block the generally N-trending terrane boundaries, most of Mesozoic age, in southern Mexico. In particular, the Mesozoic Juarez terrane appears to have no counterpart in the Chortis block: perhaps it terminated before reaching the Chortis block (Keppie, 2004) Subsequently, Rogers *et al*. (2007a) correlated a magnetic anomaly along the boundary between the southern and central Chortis terranes with the Mesozoic Teloloapan arc along the eastern margin of the Guerrero terrane (Figure 7). On the basis of this anomaly, Rogers *et al*. (2007a) inferred that the southern Chortis terrane was underlain by a Mesozoic oceanic arc, however, such rocks are not exposed. They also correlated Cretaceous arc volcanic rocks represented by the Manto Formation in Honduras with the Teloloapan arc in the Guerrero terrane, based on multi-elemental geochemical patterns. However, the distribution of the Manto Formation rocks north of the magnetic boundary between the southern and central Chortis terranes does not match, after restoration, that of most Cretaceous arc magmatic rocks in southern Mexico west of the magnetic boundary (Figure 7).

Another line of evidence cited by Rogers *et al.* (2007a) to support the traditional model is the alignment of Laramide structures in both regions, which can be restored by counterclockwise rotation of the Chortis block. This interesting fact needs to be further evaluated, especially because such structures are absent in the Chiapas region. There are different alternatives for the interpretation of this gap in the regional Laramide trend, but the simplest would be to restore the Chortis block to some position southwest of Chiapas and not necessarily southwest of the Guerrero-Oaxaca margin. Furthermore, correlatives of the NE-trending, Laramide, Colon fold-and-thrust belt of the eastern Chortis block (Rogers *et al*., 2007b) might correlate with the generally N-trending Laramide orogen in Mexico, however oroclinal bends make such constraints debatable, especially because the Laramide fold-and-thrust belt along the southern margin of the Maya block trends E-W (Ortega-Obregón *et al*., 2008).

Silva-Romo (2008) correlated the sinistral Mesozoic Guayape fault in the Chortis block with the Papalutla thrust in southern Mexico. However this reconstruction has been questioned by Keppie (2008) because the Nicaragua Rise (generally regarded as part of the Chortis block: *e.g.*, Ross and Scotese, 1988; Pindell *et al*., 1988, 2006) overlaps the Maya block. This reconstruction is inconsistent with the shape and orientation of the Cayman Trough that suggest an average rotation pole in the southern hemisphere.

An older potential piercing point is the NW-trending Permian Chiapas batholith in the Maya block (Weber *et al*., 2007). A Permo-Carboniferous pluton in the basement rocks of northern Honduras at 88°W could be a potential correlative (Horne *et al*., 1990). Similarly, the Permian dextral Caltepec fault that separates the Paleozoic Acatlán and *ca.* 1 Ga Oaxacan complexes in southern Mexico (Elías-Herrera and Ortega-Gutiérrez, 2002; Keppie *et al*., 2008) has not been identified in the Chortis block.

Thus, the identification of piercing points that can be matched between southern Mexico and the Chortis block remains elusive. This may be due to the vertical axis rotations during the Cretaceous inferred by Gose (1985).

b) Age, distribution and extinction patterns of Cenozoic arc magmatic rocks

The age and distribution of plutonic and volcanic arc rocks in both southern Mexico and the Chortis block may be used to infer paleogeographic reconstructions. Truncation of the continental margin of southern Mexico is indicated by the proximity of Paleogene calc-alkaline, arc plutons and the Acapulco trench. In the traditional model, the missing forearc is inferred to have been located in and removed with the eastward migrating Chortis block (Bellon *et al*., 1982, Schaaf *et al*., 1995). One implication of this model is a post-early Oligocene eastward migration of a trench-trench-transform (T-T-F) triple point and the related arcs (Ratschbacher *et al*., 1991; Herrmann *et al*., 1994; Schaaf *et al*., 1995). The southeastward displacement of the T-T-F triple point at the trailing edge of the Chortis block is also inferred to have produced the gradual extinction of arc magmatism along the present-day continental margin of Mexico and its later onset (early Miocene) along the Trans-Mexican Volcanic Belt (Ratschbacher *et al*., 1991; Schaaf *et al*., 1995; Ferrari, 1999; Morán-Zenteno *et al*., 1999). In this model, a moderately dipping Benioff zone beneath the Chortis block changes to a gently dipping Benioff zone beneath southern Mexico. The northwestern edge of the subducting slab beneath the Chortis block is inferred to have produced short-lived, arc magmatism localized along the southern margin of Mexico that migrated eastwards with the triple point. The decreasing age pattern in the extinction of arc magmatism in southern Mexico displays two segments with different rates of migration (Schaaf *et al*., 1995) (Figure 8). The first segment extends for about 700 km from Puerto Vallarta to Acapulco and displays, according to our calculations, an extinction

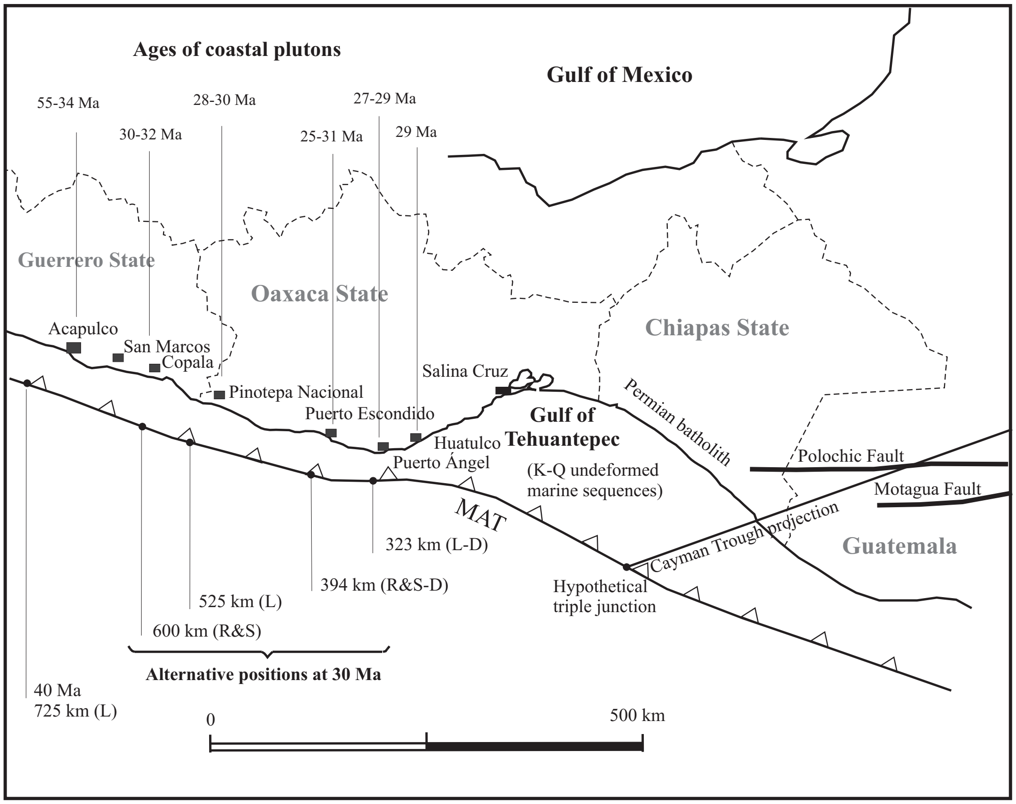

Figure 5. Sketch map of the continental margin of southern Mexico showing alternative positions of the North America-Caribbean-Farallon triple junction at 30 Ma in the hypothesis of the Chortis block adjacent to southern Mexico. Positions calculated using different spreading rates for the Cayman Trough. L: data from Leroy *et al.* (2000); L-D: data from Leroy *et al.* subtracting 206 km of internal deformation in Chiapas and the Chortis block; R&S: data from Rosencrantz and Sclater (1986); R&S-D: data from Rosencrantz and Sclater subtracting 206 km of deformation. For reference, ages of coastal plutons are also indicated. MAT=Middle America Trench.

migration rate of 11 mm/yr. The second segment extends 500 km from Acapulco and Tierra Colorada to Huatulco, and on the basis of the zircon dates published by Herrmann *et al.* (1994) and Ducea *et al*. (2004), this second segment displays a rapid migration rate of at least 100 mm/yr. This rate is confirmed by the coeval volcanic inland counterparts of Guerrero and Oaxaca (Morán-Zenteno *et al*. 2000 and references therein). This latter rate is about five times greater than 17–29 mm/yr rate calculated for the simistral motion across the Cayman Trough (Rosencrantz and Sclater, 1986; Leroy *et al*., 2000) for this time interval, suggesting that the extinction of arc volcanism and the margin truncation of southern Mexico are not related to migration of the Chortis block. Furthermore, restoring the motion of the Chortis block relative to southern Mexico, subtracting *ca.* 200 km of intraplate deformation, yields different locations for the inferred T-T-F point at 30 Ma (Figure 5): (1) *ca.* 400 km migration of the T-T-F point along the present-day trench during the last 30 Ma would locate the northwestern tip of the Chortis block near Puerto Escondido; and (2) using the spreading rate of 17 mm/yr for the Cayman Trough for the last 25 Ma and 20 mm/yr for 25–30 Ma (Leroy *et al*., 2000), the T-T-F point would be located in an even more southeastern position, near Puerto Angel. It has been inferred that extinction age of arc magmatism along the continental margin of Guerrero and Oaxaca states migrated with the T-T-F point (Herrmann *et al*., 1994; Schaaf *et al*., 1995). However, *ca*. 30 Ma and younger coastal plutons at Cruz Grande, San Marcos, Pinotepa Nacional and Pochutla have been recorded (Herrmann *et al*., 2004; Ducea *et al*., 2004) well to the west of the inferred triple point (Figure 5), which is incompatible with margin truncation caused

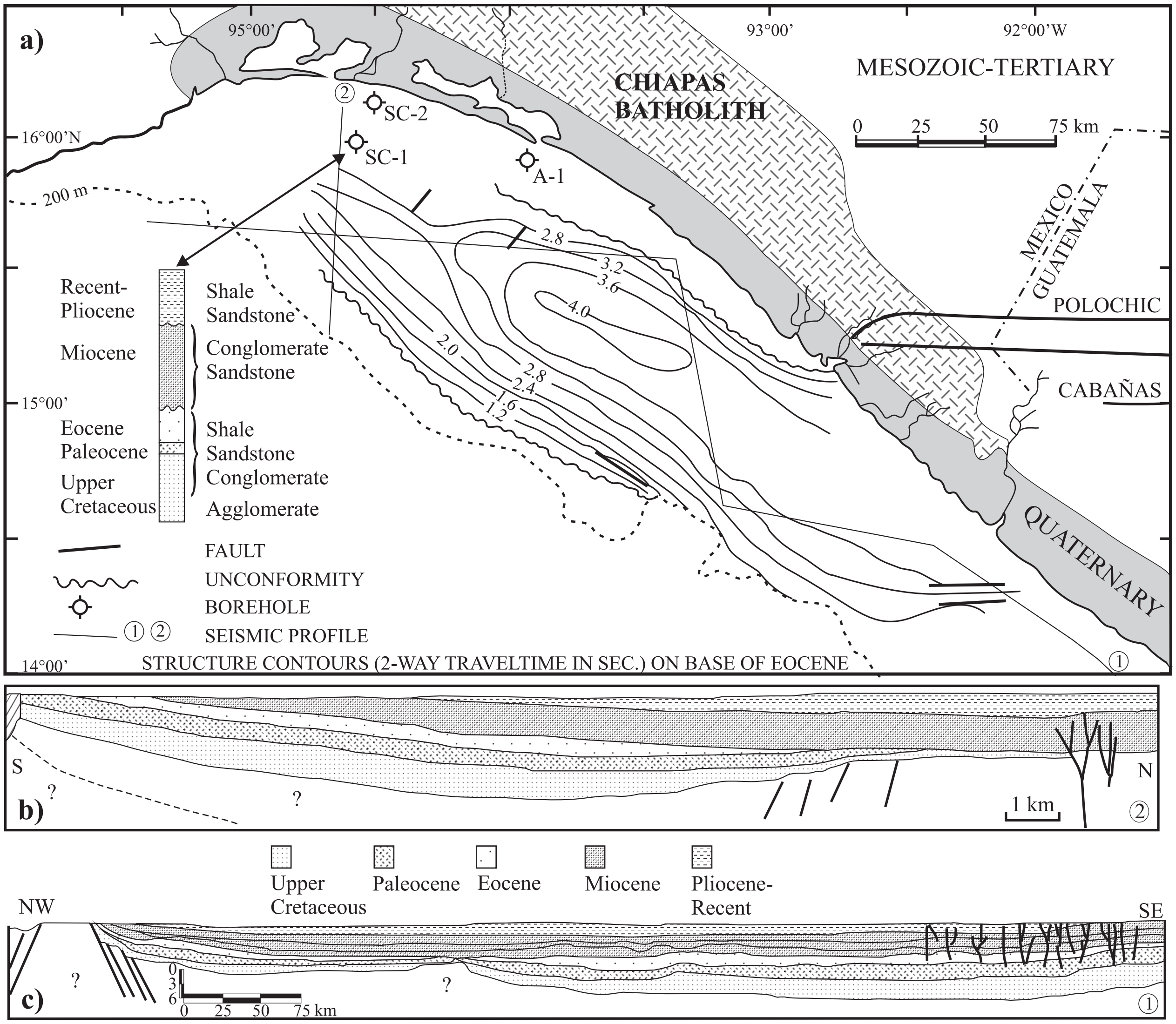

Figure 6. (a) Map of the Gulf of Tehuantepec and neighboring coastal area showing structure contours (two-way travel time in seconds) on the base of the Eocene and log of drill core (after Sánchez-Barreda, 1981). Note the absence of fault displacement across the projected trace of the Polochic-Motagua fault zone; (b) and (c) sections based on reflection seismic profiles located on (a) interpreted by Sánchez-Barreda (1981).

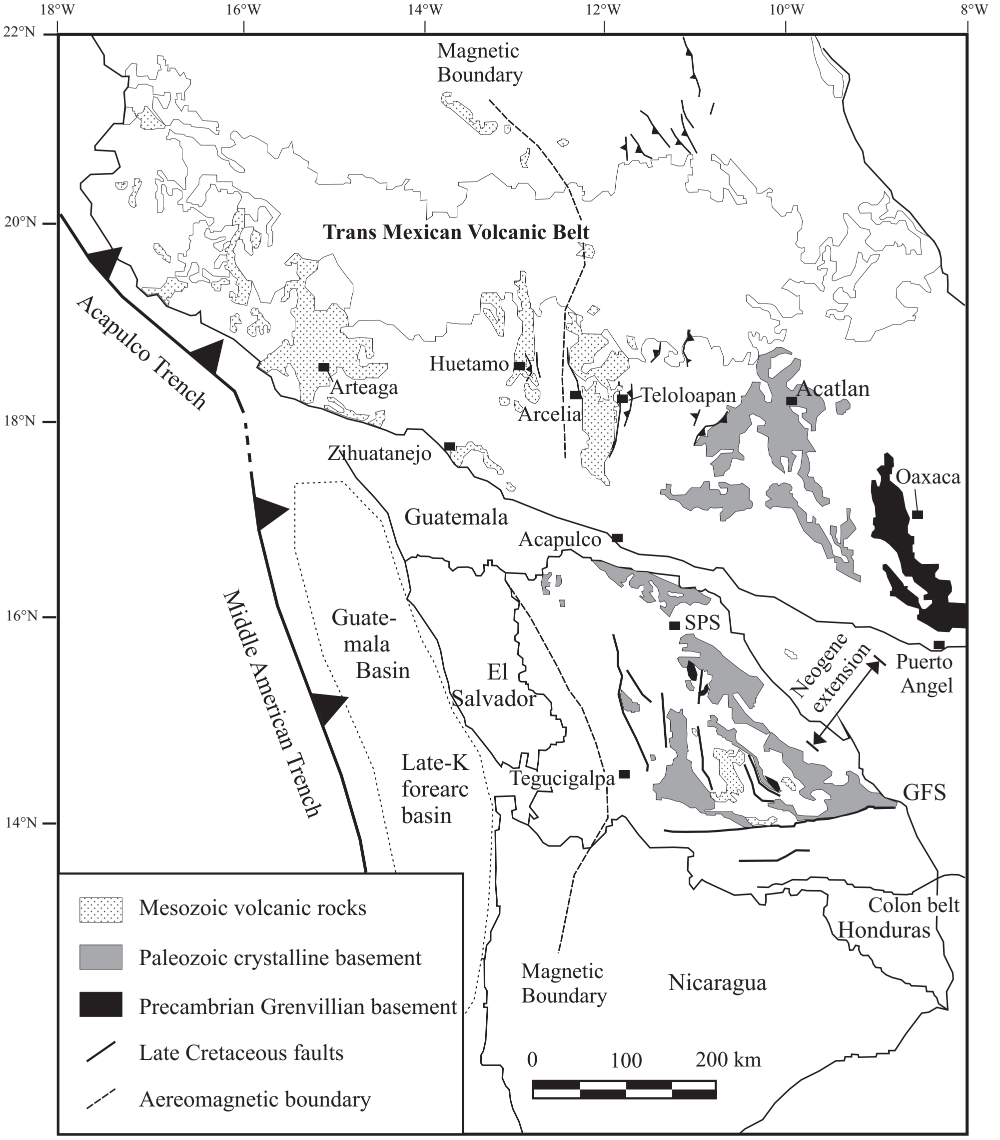

Figure 7. Reconstruction of the Chortis block to a position adjacent to southern Mexico according to Rogers *et al.* (2007a). Figure modified to show only the Mesozoic arc-volcanic rocks and Paleozoic and Precambrian basements. SPS: San Pedro Sula, GFS:Guayape fault system.

by migration of the Chortis block. An alternative model proposed by Keppie *et al.* (in press) suggests that the forearc was removed by subduction erosion. Reconstructing the lost forearc, places the trench *ca.* 220 km to the southwest of the present Middle American trench; such a conclusion is compatible with the Pacific model, but incompatible with the traditional model.

The northern Chortis block is made up of a ~100 km wide east-west magmatic arc with ages ranging from Late Cretaceous to early Cenozoic. This magmatic zone is associated with sheared high grade gneiss. Most ages of these magmatic rocks fall between 54 and 92 Ma (Horne *et al.*, 1976a, 1976b, 1990; Manton, 1996; Rogers *et al.*, 2007a and references therein) and not 34–29 Ma, as is typical for the Acapulco-Huatulco margin (Figure 8). Arguing in favor of a Chortis-southern Mexico connection, Rogers *et al.* (2007a) suggested that the northern Chortis magmatic zone and the Xolapa terrane of southern Mexico (Acapulco-Huatulco continental margin) have a common origin, however the age ranges of magmatic rocks are different. Late Cretaceous-Paleocene magmatic plutons in southern Mexico are more typical along the continental margin northwest of Acapulco, especially in Jalisco and Colima (Schaaf *et al.*, 1995), where they display an eastward decreasing age trend. Although there are reports of some deformed Paleocene plutons in the Acapulco-Tierra Colorada area, the batholiths are predominantly ~34 Ma (Herrmann *et al.*, 1994; Ducea *et al.*, 2004; Solari *et al.*, 2007). The northern Chortis magmatic zone could represent the southeastward continuation of the plutonic rocks of Jalisco and Colima, however, the absence of gneisses in the Xolapa Complex makes this correlation uncertain.

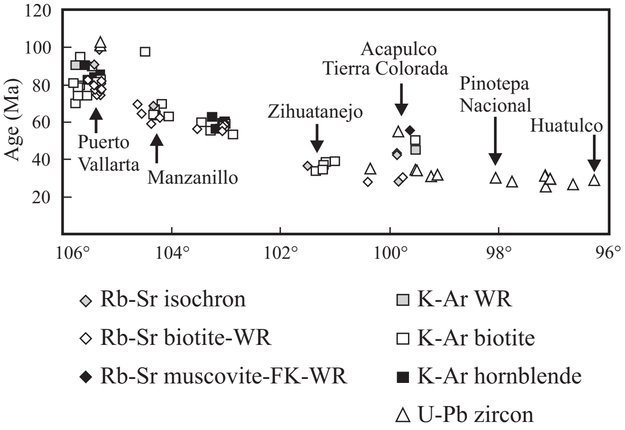

Figure 8. Ages *vs*. distance plot showing the geochronology of magmatic rocks along the present-day continental margin of southern Mexico. For clarity only U-Pb ages are shown for the Acapulco-Huatulco segment. Data from Herrmann *et al.* (1994); Schaaf *et al.* (1995); Morán Zenteno *et al.* (2000 and references therein); Ducea *et al.* (2004); Solari *et al.* (2007).

Third order

a) Age, configuration, trends and distribution of tectonic features, magmatic provinces and sedimentary basins

Among the most remarkable Cenozoic, third order, structural features in the Sierra Madre del Sur, especially near the coastal zone, are WNW and E-W oriented, normal and left lateral shear zones (Ratschbacher *et al*., 1991; Riller *et al*., 1992; Tolson *et al*., 1993; Meschede *et al*., 1997). In the Tierra Colorada region, a WNW-trending shear zone predates late Eocene plutons (~34 Ma) and postdates *ca*. 55 Ma granites (Herrmann *et al*., 2004; Ducea *et al*., 2004; Solari *et al*., 2007), whereas in the Huatulco region an E-W, sinistral shear zone cuts a 29 Ma pluton and is intruded by 23 Ma hypabyssal rocks (Tolson *et al*., 1993; Tolson, 2007). Although these shear zones were active at different times, they have generally been interpreted in terms of sinistral, transtensional tectonics associated with detachment and southeastward displacement of the Chortis block (Ratschbacher *et al*., 1991; Tolson *et al*., 1993; Herrmann *et al*., 1994). However, such observations are open to other explanations, such as oblique plate convergence. Thus, these data are not unique to any of the existing models.

If the Chortis block has been part of the Caribbean plate since the Eocene, the traditional model implies that it was attached to the continental margin of Guerrero and Oaxaca. Assuming that it was rotated about an average pole near Santiago (Chile) (Jordan, 1975), the southward convexity of the Acapulco-Motagua-Cayman boundary would have produced transpressional effects in the continental margin of Mexico. Cerca *et al*. (2007) have recorded a transpressional episode in the Guerrero continental margin of Paleocene-early Eocene age, however, this predates the Chortis displacement along the continental margin of Mexico inferred for the traditional model. The contractional features documented in the Tierra Colorada area, north of Acapulco (Solari *et al*., 2007), emerge as the only possible pre-Miocene effects of such a mechanism but they are restricted to a relatively small region. In Oaxaca State, no transpressional features have been documented, and instead, transtensional or strike-slip mechanisms have been interpreted in Cenozoic shear zones (Tolson *et al*., 1993; Ratschbacher *et al*., 1991; Corona-Chávez *et al*., 2006). The Miocene Chiapas fold-and-thrust belt and the associated left lateral faults post-date any inferred passage of the T-T-F triple point and have been interpreted in terms of collision of the Tehuantepec Ridge with the trench (Mandujano-Velázquez and Keppie, in press).

b) Age, petrology and distribution of pre-Mesozoic basement rocks

Additional third order arguments that have been cited in support of a traditional model include: (1) the similarity of the Mesozoic stratigraphy, especially the Cretaceous platformal carbonates (Rogers *et al*., 2007a; Silva-Romo, 2008); and (2) the apparent similarity of the *ca*. 1 Ga metamorphic basements in Oaxaquia and in the central and northern Chortis terranes (Pindell and Dewey, 1982; Ross and Scotese, 1988; Manton, 1996; Keppie *et al*., 2003; Solari *et al*., 2003; Rogers *et al*., 2007a) (Figure 7). However, the metamorphic grade is different: granulite facies in the Oaxacan Complex versus amphibolite facies in the Chortis block. Regardless, these correlations merely indicate proximity and do not tightly constrain the paleogeographic reconstructions. Thus, they can be accommodated by any of the existing models.

CONCLUSIONS

In order to bring some objectivity to the debate about the Paleogene paleoposition of the Chortis block relative to southern Mexico, data and features are evaluated in terms of a hierarchical ranking and reveal the following conclusions:

(i) whereas both the traditional and Pacific models are consistent with 1st order plate tectonic features in the Cayman Trough, they are not satisfied by the *in situ* model;

(ii) all models are within the errors provided by 1st order existing paleomagnetic data;

(iii) an essential 1st order element, the undeformed Upper Cretaceous-Quaternary sediments in the Gulf of Tehuantepec, can be accommodated by either the Pacific or *in situ* models: it provides a fatal blow to the traditional model;

(iv) Second order features, such as piercing points and arc-related rocks provide no unequivocal constraints on the location of the Chortis block;

(v) Third order data merely indicate that the Chortis block and southern Mexico were proximal, but provide no unique features to more tightly constrain the paleogeographic reconstructions.

Given this assessment, the only model that satisfies all the 1st order features is the Pacific model, and it can accommodate all of the 2nd and 3rd order categories. However, the Pacific model published by Keppie and Morán-Zenteno (2005) requires the following modification: (a) subtract the 200 km intraplate deformation in the relative displacement between the Chortis and Maya blocks; and (b) allow for a small ocean basin, at least 100 km, between the Chortis and Maya blocks in the Late Cretaceous: this would place the Chortis block south of the Gulf of Tehuantepec and the Eocene-Oligocene forearc lost to subduction erosion (Keppie *et al*., in press). Latest Cretaceous-Eocene collision of the Chortis and Maya blocks is inferred to have closed the small ocean basin leaving an ophiolitic suture along the Motagua fault zone and obducted ophiolitic on the Maya block (Giunta *et al*., 2006). Clearly further work is required to provide better Mesozoic reconstructions.

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