

**Geomorphic analysis
of landscapes from
northern Central
America**

L. Andreani and
R. Gloaguen

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Geomorphic analysis of transient landscapes from the Sierra Madre de Chiapas and Maya Mountains (northern Central America): implications for the North American–Caribbean–Cocos plate boundary

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Abstract

We use a geomorphic approach in order to unravel the recent evolution of the diffuse triple junction between the North American, Caribbean, and Cocos plates in northern Central America. The complex tectonic setting produced an intricate pattern of landscapes that we try to systemize using remote sensing tectonic geomorphology and available geological and geophysical data. We classify regions with specific relief characteristics and highlight uplifted relict landscapes in northern Central America. We also analyze the drainage network from the Sierra Madre de Chiapas and Maya Mountains in order to extract information about potential vertical displacements.

Our results suggest that most of the landscapes of the Sierra Madre de Chiapas and Maya Mountains are in transient stage. Topographic profiles and morphometric maps highlight elevated relict surfaces that are characterized by a low amplitude relief. The river longitudinal profiles display upper reaches witnessing these relict landscapes while lower segments characterized by multiple knickpoints, that adjust to new base-level conditions.

These results backed by published GPS and seismotectonic data allow us to refine and extend existing geodynamic models of the triple junction. Relict landscapes are delimited by faults and thus result from a tectonic control. The topography of the Sierra Madre de Chiapas evolved as the result of (1) the inland migration of deformation related to the coupling between the Chiapas Massif and the Cocos fore-arc sliver, and (2) the compression along the northern tip of the Central America Volcanic Arc. Although most of the shortening between the Cocos fore-arc sliver and the North American plate is accommodated within the Sierra de Chiapas and Sierra de los Cuchumatanes, a small part may be still transmitted to the Maya Mountains and the Belize margin through a “rigid” Petén basin.

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1 Introduction

The aim of this work is to examine geomorphic features along two key areas (the Sierra Madre de Chiapas and the Maya Mountains, Fig. 1) in order to better understand the interactions between tectonics and landscapes within the Cocos–Caribbean–North American triple junction. In active orogens, landscapes result from a competition between vertical uplift, which modifies the base-level of rivers, and erosional processes, which result in the progressive rejuvenation of topographic features through time (e.g., Mather, 2000; Snyder et al., 2000). Geomorphic indices are commonly used to detect the response of landscapes to recent deformation processes (Burbank and Anderson, 2001; Keller and Pinter, 1996, and references therein). In addition, an increasing number of algorithms and toolboxes were developed during the last decade in order to extract these indices from digital elevation models and to analyze landscapes (e.g., Schwanghart and Kuhn, 2010; Shahzad and Gloaguen, 2011a).

Tectonic evolution of northern Central America (Fig. 1) is related to the triple junction between the North American, Caribbean, and Cocos plates (e.g., Malfait and Dinkelmann, 1972; Burkart, 1983; Guzmán-Speziale et al., 1989; Lyon-Caen et al., 2006; Ratschbacher et al., 2009; Authemayou et al., 2011). The oceanic Cocos plate is subducted beneath the North American and Caribbean plates along the Middle America Trench. Convergence rates increase southward from $\sim 50 \text{ mm yr}^{-1}$ offshore southern Mexico to $\sim 80 \text{ mm yr}^{-1}$ offshore Nicaragua (DeMets and Wilson, 1997; DeMets, 2001). The North American–Caribbean plate boundary is a sinistral transform system which accommodates the eastward escape of the Caribbean plate at an estimated rate of $18\text{--}20 \text{ mm yr}^{-1}$ (Dixon et al., 1998; DeMets et al., 2000; Lyon-Caen et al., 2006). This transform system does not connect to the trench. Indeed, recent works indicate that both the Caribbean and North American plates are limited to the west by a forearc sliver which is coupled to the mechanically strong Cocos slab (e.g., Turner et al., 2007; Phipps-Morgan et al., 2008). Current models agree on the fact that the dextral Jalpatagua fault (Fig. 2) represents the limit between the forearc sliver and the Caribbean

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is lost within the Central America volcanic arc (e.g., Guzmán-Speziale et al., 1989; Guzmán-Speziale and Meneses-Rocha, 2000). In the east, the Polochic-Motagua fault system connects to the Swan Islands transform which forms the southern branch of the Cayman spreading center in the Caribbean Sea (e.g., Rosencrantz and Sclater, 1986; Heubeck and Mann, 1991).

These faults are seismically active (Fig. 3a; White, 1984; Singh et al., 1984; Ambraseys and Adams, 1996; Guzmán-Speziale, 2010) and Quaternary displacements are documented (e.g., Burkart, 1978, 1983; Authemayou et al., 2012). Using regional drainage patterns, (Burkart, 1978) proposed a 135 km horizontal offset along the Polochic fault. However, this estimate was recently challenged by Brocard et al. (2011) which propose only 25 km for the last 7–10 Ma. Recent works argue for significant vertical displacements along the Polochic and Ixcán faults (Authemayou et al., 2011, 2012). Brocard et al. (2011) described a relict Middle Miocene planation surface which formed at low elevation and covered most of the Polochic-Motagua sliver (the so-called “Mayan paleosurface”). This surface was subsequently uplifted and deformed. Using this surface as a marker, Authemayou et al. (2011) estimated the crustal shortening between 17 and 35 km along the western segment of the Polochic fault (Fig. 2), where the 13–7 Ma old Mayan paleo-surface rests on top of the Sierra de los Cuchumatanes at a maximum elevation of 3800 m.

The Polochic fault have been considered as the main North American-Caribbean plate boundary between 10 and 4 Ma before being overtaken by the Motagua fault (Burkart, 1978; Deaton and Burkart, 1984). Using a model of elastic deformation derived from GPS measurements, Lyon-Caen et al. (2006) suggest that the Motagua fault accommodates 75 % of the present-day interplate motion while the Polochic fault seems to accommodate less than 25 %. GPS data also indicate that the slip rate along the Polochic fault decreases from 5 mm yr^{-1} in the east to ~ 0 near its western termination. However, the Polochic and Ixcán faults show a denser historical seismicity (Guzmán-Speziale, 2010; Authemayou et al., 2012, and references therein).

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to the west while strike-slip motion is absorbed at their eastern terminations by thrusting and folding. The Chiapas frontal fold-and-thrust belt is located between the Sierra de Chiapas and the western border of the Yucatán platform. It is constituted by closely spaced faulted folds which are rooted in shallow levels (Witt et al., 2012b).

Thermochronological, tectonic and stratigraphic evidences suggest that renewed exhumation and topographic growth occurred along the Chiapas region during the middle Miocene (16–10 Ma) and late Miocene-Pliocene (6–5 Ma), following a phase of rapid exhumation to upper crustal levels at ~ 30 Ma (Ratschbacher et al., 2009; Witt et al., 2012a). The Tonalá shear zone may have accommodated significant deformation since 16 Ma while the displacement along the transpressive Tuxtla and Malpas faults occurred during the last 6–5 Ma and could have reached 50–70 km, involving 0.5–0.8 cm.yr⁻¹ of left-lateral motion (Meneses-Rocha, 2001; Witt et al., 2012b).

2.3 Maya Mountains and Belize margin

The Maya Mountains and the Belize margin are located north to the Polochic-Motagua fault system and east to the Yucatán platform. Due to a dense vegetation cover and scarce roads, this region was seldom studied in comparison with other areas related to the North American–Caribbean plate boundary.

The eastern border of the Yucatán peninsula is crosscut by a series of NNE-trending normal faults (e.g., Weidie, 1982, 1985), which are referred as East Yucatán fault zone (EYFZ) in Fig. 2. The fault zone is ~ 80 km wide and extends over 500 km between the NE tip of the Yucatán peninsula and the Maya Mountains. The surface expression of this fault zone is seen in the alignment of topographic scarps, hydrological features (cenotes, lakes and rivers) and coastal bays (Weidie, 1985; Lesser and Weidie, 1988; Bauer-Gottwein et al., 2011). The East Yucatán fault zone represents the onshore continuation of an extensive horst and graben system which affects the western margin of the Yucatán Basin (Weidie, 1985; Rosencrantz, 1990).

According to Rao and Ramanathan (1988) and Purdy et al. (2003), the Maya Mountains correspond to a roughly NE-trending structural high where the Paleozoic base-

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ment is uplifted. Paleozoic rocks constitute the highest elevations of the Maya Mountains. The orogen mainly consists in metamorphosed Late Carboniferous to Middle Permian volcano-sedimentary rocks overlying Late Silurian granites and are bounded by the Northern and Southern Boundary faults (Kesler et al., 1974; Bateson and Hall, 1977; Steiner and Walker, 1996). The Maya Mountains are delimited by fault-bounded E- to NE-trending depressions: the Corozal Basin located to the north and the Belize Basin that borders the Maya block offshore to the east and onshore to the south. According to Purdy et al. (2003), unroofing of the Cretaceous carbonate cap of the Maya Mountains siliciclastic sediment source did not occur until late Neogene, perhaps no earlier than late Pliocene. Faulting along the Belize margin is not accurately documented. The most recent tectonic event is Pliocene or younger and the resulting structures affected Quaternary carbonate deposition. However, Lara (1993) related this event to transtensional faulting while Purdy et al. (2003) rather interpreted this event as the result of a transpression.

2.4 Models of the triple junction

First geodynamic models of the junction between the North American, Caribbean and Cocos plates consisted in a simple transform-trench boundary. For instance, Burkart (1983) proposed a model in which the Polochic fault (and perhaps also the Motagua fault) connected to the Middle America trench. He proposed that the 300 km Neogene motion between the North American and Caribbean plates was accommodated by left-lateral slip along the Polochic and Motagua faults and by extension within the depressions of Honduras and Guatemala. The slip between these two plates was compensated by a left-lateral offset of the trench.

Later works challenged the idea of a junction between the Polochic-Motagua fault system and the trench. Indeed, the Polochic fault trace terminates within the Chiapas Massif and the Motagua fault trace is lost within the Central America volcanic arc (e.g., Guzmán-Speziale et al., 1989; Guzmán-Speziale and Meneses-Rocha, 2000). As a result, more recent models (Fig. 4) argue that the motion between the North American

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and Caribbean plates does not result in an offset of the trench but is rather absorbed onshore within a complex zone of deformation. However, there is no clear consensus on the geometry of the plate boundary and on how the deformation is distributed inland.

Using seismotectonic data, Guzmán-Speziale and Meneses-Rocha (2000) proposed a model in which the Polochic-Motagua fault system is unable to propagate across the Chiapas Massif. As a result, a part of the motion between the North American and Caribbean plates is absorbed by the reverse and strike-slip faults of Chiapas (Fig. 4a). In this model, the reverse faults act as a fault jog between the strike-slip faults and the Polochic-Motagua fault system. Later on, Guzmán-Speziale (2001) suggested that part of the plate motion is also absorbed by the grabens of Central America, south of the Motagua fault (Fig. 4a).

A second category of models mainly focused on the extensional province located south of the Motagua fault. Gordon and Muehlberger (1994) proposed a model in which the Chortis block is stretched and rotating counterclockwise along the dextral Jalpatagua fault, which affects the volcanic arc (Fig. 2), and the Guayape fault in Honduras. However, more recent works suggest that dextral slip along the Central America volcanic arc is in fact related to a slip partitioning along the trench (e.g., DeMets, 2001; Turner et al., 2007; Correa-Mora et al., 2009). Using GPS data (Fig. 3b), Lyon-Caen et al. (2006) proposed a model of the plate boundary which took into account both the extensional province and the forearc sliver. They suggested that the eastward escape of the Caribbean plate was accommodated by dextral slip along the Jalpatagua fault, sinistral slip along the Polochic-Motagua fault system and by extension within the grabens of Central America (Fig. 4b). This model was refined by Franco et al. (2012) which proposed a difference in coupling along the subduction interface (Fig. 4b) in order to explain the GPS velocity field in southern Mexico (Fig. 3b). However, these two models did not address the tectonic evolution of the Sierra Madre de Chiapas.

Latest models attempted to explain both the eastward escape of the Caribbean plate as described by Lyon-Caen et al. (2006) and tectonics of the Sierra Madre de Chiapas. Andreani et al. (2008b) suggested a connection between the strike-slip faults of Chia-

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pas, the Veracruz shear zone which affects the Veracruz basin further north, and the transtension of the Mexican volcanic arc. They proposed that these three zones represent the boundary of the so-called “Southern Mexico block” (Andreani et al., 2008a). In their model (Fig. 4c), the dynamic of the plate boundary is driven by the escape of the Caribbean plate and by the counterclockwise rotation of the Southern Mexico block. However, this model does not solve the interactions between the Southern Mexico block and the Central America forearc sliver. An alternative model was proposed by Authemayou et al. (2011), in which the Central America forearc sliver extends offshore southern Mexico (Fig. 4d). In their model, the eastward escape of the Caribbean plate induces a counterclockwise rotation of the forearc sliver and a “zipper” process (i.e., progressive suturing) between the Jalpatagua and Motagua fault as the space between the two faults is left “empty” by the moving Caribbean plate. According to their model, the Tonalá Shear Zone is a suture resulting from this “zipper” process. However, both the Motagua and Jalpatagua fault traces are lost west of 91° W. The western termination of both faults seems to be associated with extension along the Guatemala City graben (Lyon-Caen et al., 2006). Furthermore, the Tonalá Shear Zone clearly connects to the Polochic Fault (Fig. 2, Guzmán-Speziale et al., 1989; Guzmán-Speziale and Meneses-Rocha, 2000).

In summary, current views on the plate boundary agree on the fact that the North American and Caribbean plates are limited by a forearc sliver to the west. The counterclockwise rotation of the forearc sliver results in transpression north of the Polochic-Motagua fault system while the eastward escape of the Caribbean plate is accommodated by the strike slip motions of the Motagua and Jalpatagua fault and by extension along the grabens of Ipala and Guatemala city. However, the connections between the western corner of the Caribbean plate and the transpressional tectonics of the Sierra Madre de Chiapas are still unclear. In addition, none of these recent models attempted to integrate the recent tectonics of the Maya Mountains and Yucatán peninsula into the dynamic of the plate boundary.

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3 Geomorphic analyses: methods and tools

3.1 Swath topographic profiles

Swath topographic profiles condense elevation data of a complex region into a single profile. Topography is extracted from a rectangular swath rather than a simple line, as in conventional profiles. Elevation data are then projected onto a vertical plane parallel to the longitudinal axis of the swath rectangle, and statistical parameters (usually the maximum, minimum and mean elevations) are calculated. The curve for maximum elevations corresponds to the ridgelines and helps to identify topographic features, such as relicts of paleo-surfaces. The curve for minimum elevations corresponds to the valley floors or river beds. A quick estimate of the incision is given by the arithmetic difference between the maximum and minimum elevations in a given longitudinal distance (window).

Swath topographic profiles were extracted from 3arcsec SRTM data from CIAT (Jarvis et al., 2008) using a MATLAB script. The swath width was fixed to 20 km. This width is large enough to contain both elevated surfaces and major rivers and small enough to avoid topographic features that are too oblique with respect to the swath axis. Elevation data were sampled using ~ 220 parallel profiles separated by 90 m. Elevations along each individual profile were also sampled using a 1 pixel (90 m) interval.

3.2 Surface analyses

The combined use different morphometric indices proves to be an efficient way to classify landscapes according to their state of dynamic equilibrium (e.g., Andreani et al., 2014; Domínguez-González et al., 2015). Hypsometric integral (HI) efficiently highlights topographic scarps, surface roughness (SR) substantially increases with incision and relief anomaly (RA) and surface index (SI) highlight elevated low relief landscapes.

The hypsometric integral shows the distribution of landmass volume remaining beneath or above a basal reference plane (Strahler, 1952; Schumm, 1956). According to

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opposite side of the range is gently dipping towards the NE. The curve for minimum elevations also indicates that rivers flowing towards the inner part of the Sierra Madre de Chiapas have a gentle gradient in comparison with those flowing into the Pacific.

The Central Valley (profiles 2 and 3, Fig. 5) corresponds to a ~ 40 km wide depression. Despite a mean elevation of ~ 600 m the local incision appears to be less than 100 m. The topographic scarp associated to the Concordia fault is barely marked. In contrast, La Venta fault and the Tuxtla fault delimitate a ~ 1500 m topographic high (referred as “La Venta block”, profile 1 in Fig. 5) which acts as a barrier for rivers coming from the Chiapas Massif.

In profile 1, the Tuxtla and Malpaso faults represent the boundary between the La Venta block and the Chiapas fold–and–thrust–belt. In profiles 2 and 3 The Tuxtla fault represents the limit between the Central Valley and two topographic highs: the Sierra de Chiapas and the Comitán High. The Sierra de Chiapas forms an impressive bulge which dominates both the Central Valley and the Chiapas fold–and–thrust–belt. Its central area is relatively flat and culminates at ~ 2500 m. The topography of the Comitán High is flat with very low incision by the drainage network and the mean elevation is ~ 1600 m. This flat surface is limited to the east by a topographic high (referred as “Leyva Velázquez block”, profile 3 in Fig. 5) which belongs to the Chiapas fold–and–thrust–belt. While in profile 1 the elevation of the fold–and–thrust–belt is constant, in profiles 2 and 3 the topography of the belt is asymmetric and elevations gently decrease toward the flat Tabasco coastal plain.

In profile 4 the volcanic arc domain appears as an uplifted plateau with elevations reaching 3500 m. The curve for minimum elevations indicate that the main drainage divide is located close to the NE limit of the volcanic arc. Rivers flowing towards the Pacific deeply incised the volcanic arc as the local incision reaches up to 2500 m. The region beyond the volcanic arc consists in a relatively flat depression which may in fact represent a back-arc plateau (profile 4 in Fig. 5). This area shows a moderate incision by the drainage network in comparison with the volcanic arc and the Sierra de los Cuchumatanes. The curve for minimum elevations suggests a significant base-

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level drop between rivers flowing within the inner part of the back-arc plateau and the drainage associated to the Polochic fault trace. The Sierra de los Cuchumatanes is bounded by two impressive scarps associated to the Polochic and Ixcán faults. The general topographic trend as well as the asymmetry of the drainage may indicate a tilt towards the NE. The Sierra de los Cuchumatanes is also deeply incised with local incision values up to 1500 m. Finally, the flat and regular topography of the Petén basin contrasts with the elevated and incised topography of the others areas.

4.1.2 Maya Mountains

In topographic profile (Fig. 6) the Maya Mountains are delimited by two major scarps related to the NE-trending Southern Boundary fault and the two NE- and E-trending Northern boundary faults. The topography of the Maya Mountains is asymmetric and the range appears slightly tilted towards the NW. The main drainage divide as well as highest elevations (up to 1000 m) are located close to the Southern Boundary fault. As indicated by the curve for local incision (Fig. 6), the areas located East of the main drainage divide are more eroded (up to 750 m of incision) in comparison with the areas located on the other side of the drainage divide where the main river incised the initial topography by 300–400 m.

The topography of the Yucatán platform (Fig. 6) appears to be controlled by the NE-trending Eastern Yucatán Fault Zone. The faults are located within a ~ 80 km wide corridor and delimitate tilted blocks. Highest elevations and incisions are located close to the fault traces and decrease towards the NW. The inner part of the Yucatán platform (located west of the fault zone) is characterized by a well defined and continuous surface. This surface is poorly incised (local incision is less than 100 m) and appears to be tilted towards the NW.

4.2 Morphometric maps

The hypsometric integral values (Fig. 7a) appear to be essentially controlled by tectonic features. Highest values are mainly found along fault-related topographic scarps while lowest values are located within depressions and flat areas. In Chiapas region areas such as the coastal plain, the Central Valley and the inner part of the Comitán High are associated to low hypsometric integral values ($HI \leq 0.35$). These are flat areas as seen in swath topographic profiles. Both the Tonalá shear zone and the Tuxtla fault scarps are highlighted by higher values ($HI > 0.35$). However hypsometric integral values are significantly greater for the Tuxtla fault scarp ($HI > 0.55$).

The structural control is also obvious in some other regions. The mountain belt north to the Polochic fault displays rather high hypsometric values. Within the extensional province of Central America, structures such as the Ipala, Comayagua and Sula grabens are associated to hypsometric lows. The pattern of hypsometric values also highlights the N- to NE-trending lineaments of the Eastern Yucatán Fault Zone (e.g., Rio Hondo fault) which are located along the Belize margin.

The surface roughness map (Fig. 7b) reveals the location of strongly incised areas as well as flat surfaces. Peak values (> 1.07 in Fig. 7b) are essentially found along the central and southern part of the Tonalá shear zone, the NW tip of the Central America volcanic arc, the mountain belt located north to the Polochic fault (e.g., Sierra de los Cuchumatanes) and Las Minas range (located between the Motagua and Polochic faults). These areas are both elevated (altitudes comprised between 2500 and 4000 m) and strongly eroded. As seen in our swath topographic profiles (Fig. 5), the difference in elevation between ridges and valley floors (local incision) is comprised between 1500 and 2500 m. Intermediate surface roughness values (1.03–1.07 in Fig. 7b) are mainly found within the inner part of the Chiapas fold-and-thrust-belt, along the eastern part of the Maya Mountains and within the grabens of Central America.

As for hypsometry, the distribution of surface roughness values in the extensional province is structurally controlled. Lowest values highlights graben floors while highest

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values correspond to horsts. Lowest surface roughness values (< 1.03 in Fig. 7b) emphasize flat (i.e. low amplitude) landscapes. Some of these areas (e.g., Central Valley of Chiapas, Comitán High) correspond to elevated surfaces and plateaus observed in swath topographic profiles (Fig. 5).

Surface roughness and hypsometric integral do not allow to discriminate low relief landscapes according to their topographic elevations. For this purpose we use two additional geomorphic indices: the relief anomaly (Fig. 8a) and the surface index (Fig. 8b). Both maps give similar results regarding the distribution of elevated and low relief landscapes, which are identified by the highest relief anomaly values (> 16) in Fig. 8a and by positive (0–0.5) surface index values in Fig. 8b. Within the Sierra Madre de Chiapas, elevated and low relief landscapes are mainly located within the Central Valley of Chiapas and the areas located east of the Tuxtla fault (Sierra de Chiapas and Comitán High). The drainage system of the Chiapas Massif (consisting of large and flat valleys) is also highlighted. The two maps also show the extend of the elevated plateaus located at the northern tip of the Central America volcanic arc as well as the relatively flat landscapes of the Petén basin and Yucatán platform. In other areas, the distribution of the low relief landscapes appears more fragmented. This is the case for the areas located between the Ixcán and Motagua faults, where our maps highlight the remnants of the Mayan paleosurface described by Brocard et al. (2011).

4.3 River longitudinal profiles

Topographic uplift, subsidence or climatically-induced sea-level changes, modify the base-level of rivers and result in the progressive erosion or rejuvenation of pre-existing topographic features through time. Thus, the analysis of deviations from the typical concave-up shape of stream longitudinal profiles (i.e., knickpoints or convex segments) is a suitable approach to explore these phenomena.

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4.3.1 Tonalá Shear Zone and volcanic arc

We analyzed 36 rivers draining the western flank of the Chiapas Massif and the Central America volcanic arc (Fig. 9). We focused our analysis on the areas located between the main drainage divide and the alluvial Pacific coastal plain. Longitudinal profiles were extracted from the modeled drainage network (Figs. 9 and 10).

Figure 10 displays characteristic stream profiles. Longitudinal profiles 6 and 15 (Fig. 10) are representative of main trunk rivers located upstream of the Tonalá Shear Zone (streams and catchments 1–17 in Fig. 9). The shear zone marks the boundary between the Permian batholith of the Chiapas Massif to the northeast and the Pacific coastal plain to the southwest. The two third of the analyzed rivers display a rather smooth and graded longitudinal profile with a single concave segment (such as profile 6 in Fig. 10). The remaining rivers display a gentle knickzone which separates two main segments (such as profile 15 in Fig. 10). Profiles 23–36 (Fig. 9) drain the Central America volcanic arc domain. Half of the analyzed rivers display a prominent knickzone (such as profile 24 in Fig. 10) which separates a gently concave upper reach from a steeper lower reach. Profiles 18–22 (Fig. 9) are located within a transition zone between the two previous regions, where the NW-trending Tonalá Shear Zone connects to the E-trending Polochic fault system along a WNW-trending fault zone. The longitudinal profiles of streams 21 and 22 display two main knickzones (see profile 21 in Fig. 10). The upper knickzone extends a few kilometers upstream of the fault which makes the junction between the Tonalá Shear Zone and the the Polochic fault system. However, the lower knickzone appears more prominent and thus seems to be associated to a larger base-level change.

We extracted two parameters from analyzed longitudinal profiles in order to illustrate the along-strike changes in the geometry of rivers. The first one is the steepness index (k_{sn}) extracted from logarithmic plots of slope against area (see examples in Fig. 10). Graded profiles show a single k_{sn} value while non-equilibrated profiles are characterized by changing k_{sn} values associated to several segments. In this latest case we

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considered the k_{sn} value of the lowermost segment as it is the one along which rivers adjust to new base-level conditions (e.g., Kirby and Whipple, 2001; Wobus et al., 2006; Whittaker et al., 2008). The second parameter is the estimated base-level change. If the profile displayed a well defined upper reach, we projected the segment located

5 above the knickzone using a logarithmic plot of slope against distance (see Eq. 7). We then estimated the base-level change according to the difference in elevations between the projected and the actual profiles at the outlet (see examples in Fig. 10).

Both k_{sn} values and estimated base-level changes were plotted along a profile passing through the outlets of the analyzed catchments (Fig. 9). The results suggest a substantial alongstrike increase in k_{sn} values, from ~ 100 along the northern tip of the Chiapas Massif to > 200 along the volcanic arc. Estimated base-level changes seem to be low for the Chiapas Massif (< 200 m) but increase significantly along the southern tip of the Tonalá Shear Zone (where it connects to the E-trending Polochic fault) and are higher within the volcanic arc (1000–2000 m).

4.3.2 Grijalva river

The Grijalva river (profile 1 in Fig. 11) flows from the northern tip of the volcanic arc towards the Tabasco coastal plain. Two main knickzones are located upstream of the Necta fault. They mark the transition between the elevated volcanic arc plateau, the back-arc domain and the local base-level of the central depression of Chiapas. The reconstructed profile made using the segment located above the lowest knickzone suggests a ~ 500 m base-level fall between the back-arc domain and the central depression of Chiapas. Segments located within the central depression of Chiapas (between the Necta and Tuxtla faults) and the the Tabasco coastal plain display a lower gradient in comparison with those located upstream of the Necta fault. Despite numerous artifacts related to hydroelectric dams (e.g., La Angostura, Chicoasén and Malpaso dams) and canyons (e.g., Sumidero), we can infer a major knickzone located between the Tuxtla fault and the Chicoasén dam. The gradient of the Grijalva river is 200 m between the Tuxtla fault and the Chicoasén dam (~ 30 km apart) while it is less than

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50 m between La Angostura dam and the Tuxtla fault (~ 60 km apart). We can also fit the segments upstream and downstream of La Angostura dammed lake with a single concave line (see profile 1 in Fig. 11). The knickzone marks a ~ 350 m base-level fall between the central depression of Chiapas and the Tabasco coastal plain.

5 The Seleguá river (profile 2 in Fig. 11) is a right bank tributary of the Grijalva river which flows from the southern tip of the Sierra de los Cuchumatanes into the central depression of Chiapas. A prominent knickzone is observed upstream of the Polochic fault. This knickzone separates an upper segment with a gentle gradient ($k_{sn} < 50$) from a lower and much steeper ($k_{sn} > 300$) segment. The upper segment is associated to the relicts of the Mid-Miocene Mayan paleosurface which is preserved on top of the Sierra de los Cuchumatanes (Authemayou et al., 2011). Downstream of the Polochic fault the profile displays an overall convex shape related to numerous knickzones. The lowermost segment is located within the central depression of Chiapas and shows a gentle gradient.

15 Longitudinal profiles 3–5 (Fig. 11) are from left-bank tributaries located within the Chiapas Massif. Longitudinal profile 3 (southern tip of the Chiapas Massif) display two prominent knickzones. The upper knickzone is located close to the drainage divide and separates an upper segment with a gentle gradient ($k_{sn} < 75$) from a lower and much steeper ($k_{sn} > 150$) segment. The lower knickzone is more gentle and located downstream of the Necta fault trace. Profiles 4 and 5 intersect the lineament made by La Venta and Concordia faults. In both profiles the upper reach (60–80 km from the drainage divide) is gently concave (k_{sn} values around 30). The upper segment are limited downstream by a knickzone which correspond both to the boundary between the Chiapas Permian batholith and the Cretaceous/Tertiary sedimentary cover and to La Venta–Concordia lineament. In both profiles the knickzone is associated to canyons as the river incised through the sedimentary cover (mainly Cretaceous limestones). In profile 4 this knickzone marks a minor base-level fall (approximately 50 m) between the upper reach and the central depression of Chiapas. In profile 5 the knickzone is associated to a major base-level fall as the lower reach connects to the portion of the

4.3.4 Steepness index map

The analysis of river longitudinal profiles shows that major base-level changes (i.e., higher than 100 m) are associated to prominent knickzones and to a substantial increase in steepness index (k_{sn}) values. We propose thus to map the variations of k_{sn} values within the Sierra Madre de Chiapas in order to assess the locations of main drainage network perturbations. We computed k_{sn} values from extracted river profiles using a 5 km moving window. We then interpolated obtained values using a natural neighbor (NN) method. The result is shown in Fig. 13.

The overall distribution of k_{sn} appears to be tectonically controlled, as highest values are found close to major tectonic features. In Chiapas highest k_{sn} values (> 150 in Fig. 13) are mainly distributed along the Tuxtla fault, the E-trending strike slip faults of the Sierra de Chiapas and the portion of the fold-and-thrust belt located north of the Sierra de Chiapas. Areas located along the La Venta fault and the Tonalá Shear Zone display intermediate k_{sn} values (90–120). Uniformly low k_{sn} values suggests that most of the tributaries of the Grijalva river flowing in the northern part of the Chiapas Massif and the Central Valley of Chiapas share a common base-level.

To the south, the Polochic fault exerts a strong control over the drainage network. The Sierra de los Cuchumatanes and the SE tip of the Chiapas Massif (limited by the Polochic fault to the south and the Ixcán and Necta faults to the north) display especially high values (> 180). By contrast, most of the areas located south of the Polochic fault are associated to lower k_{sn} values (< 150). Lowest k_{sn} values (< 90) are found within the back-arc region and the graben of Guatemala City. The last area displaying high k_{sn} values (> 180 in Fig. 13) corresponds to the SW flank of the Central America volcanic arc where rivers are affected by a very steep topographic gradient.

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4.3.5 Maya Mountains

We analyzed the drainage network of the Maya Mountains using a map of isobases from rivers and several longitudinal profiles (Fig. 14). The isobases were computed by interpolating the elevations from extracted rivers with a Strahler order ≥ 2 .

Longitudinal profiles 1–5 (Fig. 14) are part of the Belize river watershed, which drain the northern and western side of the Maya Mountains. All these profiles display prominent knickpoints which mark the transition between the upper reaches which are usually gently concave and the lower segments which are either concave with a steeper gradient or convex. The knickpoints are located upstream of the ENE- to E-trending Northern Boundary fault for profiles 1–3 (Fig. 14) and upstream of a NE-trending fault zone in profiles 4 and 5 (Fig. 14). The reconstructed profiles made using the upper reaches suggest that the drainage network faced a 300–500 m base level change.

Profiles 6–9 (Fig. 14) are located in the southern and eastern parts of the Maya Mountains and flow directly into the Caribbean sea. Only southernmost profiles display prominent knickpoints which delimitate a well defined upper reach (e.g., profile 6 in Fig. 14). These knickpoints are located upstream of the NE-trending Southern Boundary fault and a ENE-trending fault zone. By contrast, most of profiles located along the eastern side of the Maya Mountains display an almost smooth and concave shape such as profile 7 (Fig. 14). In particular, there is no significant change in the gradient of the rivers along the Southern Boundary fault. However, in some cases a knickpoint associated to a relict upper reach is found close to the drainage divide (profiles 8 and 9 in Fig. 14). The reconstructed upper reaches in profiles 5 and 8 (Fig. 14) suggest a 500 m base level change.

Isobases from rivers (Fig. 14) allows to summarize the geometry of the drainage network. Within the Maya Mountains, the isobase surface forms a roughly sigmoidal-shaped plateau. Spaced contour lines indicate gentle gradient in rivers flowing in the central part of the range. The top of the isobase surface is more elevated (> 800 m) in the southern part of the Maya Mountains (between 16.30 and 16.60° N) where it

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Authemayou et al. (2011) described a relict Middle Miocene planation surface (the so-called “Mayan paleosurface”) which covered most of the areas between the Ixcán and Motagua faults (Fig. 15) and was subsequently uplifted and deformed. Our results suggest that relict landscapes are also preserved within the Sierra Madre de Chiapas and Maya Mountains. Topographic profiles (Figs. 5 and 6) and both relief anomaly and surface index maps (Fig. 8) highlight elevated areas which are characterized by a low amplitude relief. These areas are surrounded by more dissected landforms which are characterized by high surface roughness values (Fig. 7). The surface index map (Fig. 8) shows very well this dual distribution of elevated and low relief (positive values in Fig. 8) and dissected (negative values in Fig. 8) landforms. This is a clear indication that landscapes within the Sierra Madre de Chiapas and Maya Mountains are in transient stage, and morphometric maps allows to discriminate between the areas forming part of an upper-relict landscape and the propagating front of river incision. Moreover, river longitudinal profiles display an upper reach associated to these relict landscapes while lower segments represent one or several knickzones along which channels adjust to new base-level conditions.

We attempted to map the distribution of elevated relict landscapes from northern Central America (Fig. 15). The surface index and relief anomaly maps (Fig. 8) highlights well areas where elevated and low relief surfaces are extensively preserved and provide thus a good basis for mapping the extend of relict landscapes. In some areas where elevated surfaces are incised by the drainage network and for the Chiapas Masif where surfaces are nested between ridges, we refined our map using slopes and topographic contours derived from the SRTM data.

Relict landscapes from the Sierra Madre de Chiapas can be divided in four main domains. The westernmost domain consist in a monadnock-type landscape which developed over the Chiapas Massif (Fig. 15). In morphometric maps, this area is characterized by low hypsometric integral and surface roughness values (Fig. 7). In fact, these geomorphic indices respond to an extensive system of large and relatively flat valleys. The drainage system appears in steady-state as rivers display smooth concave profiles

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and low k_{sn} values (upper segments of profiles 4 and 5 in Fig. 11). The isobase surface of the rivers is extremely flat (see curves for minimum elevations in swath profiles 1 and 2, Fig. 5). Such low gradients are characteristic of lowland alluvial rivers. We interpret the topography of the Chiapas Massif as the result of a sustained erosion which resulted in the development of a low relief surface and a system of alluvial valleys. In other words, the Permian batholith of the Chiapas Massif and its sedimentary cover were incised until rivers reached an almost flat and steady-state base-level. However, this isobase surface is now located ~ 400 m above the present-day sea level. We suspect thus that the topography of the Chiapas Massif was much lower than it is today and that it has been subsequently uplifted.

The large valleys of the Chiapas Massif connects to the east to two morphological domain: the Central Valley of Chiapas and La Venta plateau (Fig. 15). The eastern boundary of these two domains corresponds to the Tuxtla and Malpaso faults. The Central Valley of Chiapas consists in gently folded tertiary sediments. The topography of this area is smooth as suggested by high relief anomaly (Fig. 8) and low surface roughness (Fig. 7) values. However, high hypsometric integral values along the Grijalva river reflect an entrenchment of the drainage network. The canyons are filled by the water of La Angostura dammed lake but their depth probably did not exceeded 150 m. The Mesozoic carbonates of La Venta plateau were uplifted and gently tilted along La Venta and Tuxtla faults. This area is also associated to an entrenchment of the drainage network. The analysis of river longitudinal profiles (Fig. 11) suggests a ~ 350 m base level change between the inner part of the Sierra Madre de Chiapas and the Tabasco coastal plain. We relate the entrenchment of the drainage network within the Central Valley of Chiapas and La Venta plateau to the uplift of the areas located between the Tuxtla fault and the Tonalá shear zone. This uplift resulted in an erosional wave propagating upstream within the drainage of the Grijalva river.

The last domain encompasses the elevated plateaus east of the Tuxtla fault (Comitán High and Sierra de Chiapas, Fig. 15). The northwest part of this plateau is heavily incised as shown by high surface roughness values (Fig. 7). By contrast, the areas south

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of the Tectapan fault appear to be less dissected. In spite of elevations up to 2400 m, surface roughness values (Fig. 7) remains low. Indeed, the top of the plateau is associated to a low relief topography which is disrupted by incisions along the E-trending faults. These differences are probably related to several factors, including lithology (the southern areas consist mainly in Mesozoic carbonates with subterranean drainage limiting surface erosion), climate (the northern areas may receive more precipitations from the Gulf of Mexico), and local base-level changes. The analysis of river longitudinal profiles (Fig. 11) suggests a $\sim 500\text{--}700$ m base level change along the Tuxtla fault and $\sim 700\text{--}1100$ m in the northern part of the Sierra de Chiapas.

The age of the relict landscapes in Sierra Madre de Chiapas is unknown. Thermochronological and stratigraphic evidences suggest two main periods of topographic growth. The first one occurred during the middle Miocene (16–10 Ma) and the latest one started during the late Miocene-Pliocene and is still ongoing (Guzmán-Speziale and Meneses-Rocha, 2000; Meneses-Rocha, 2001; Ratschbacher et al., 2009; Witt et al., 2012a). We assume that the relict landscapes of the Sierra Madre de Chiapas have developed following the middle Miocene phase of topographic growth. The development of large alluvial valleys within the Chiapas Massif suggests that the Permian batholith and its sedimentary cover were uplifted and significantly eroded until rivers reached an almost flat base-level. Indeed, Witt et al. (2012a) show that the middle to late Miocene period is associated to marked increase in erosion of the Chiapas Massif and sedimentation within the basins of the Tabasco region. The distribution of morphometric indices (Fig. 7) and the location of knickzones upstream of major faults such as the Tuxtla fault (profiles 1–3 in Fig. 12) indicate that this late Miocene erosional topography was subsequently uplifted and fragmented by tectonics. This probably happened during the latest period of deformation (~ 5 Ma to present). A middle Miocene age for the erosional topography of the Sierra Madre de Chiapas would be consistent with the timing of similar topographic features, such as the so-called “Mayan paleosurface” which covered most of the Polochic-Motagua sliver (Authemayou et al., 2011; Brocard

et al., 2011). According to Brocard et al. (2011), this widespread planation surface formed at low elevation during the middle Miocene (between 13 and 7 Ma).

Our results show that most of the Maya Mountains consist in an elevated relict landscape (Fig. 15). Geomorphic maps (Figs. 7 and 8) as well as isobases from rivers (Fig. 14) indicate that low relief surfaces have been extensively preserved in the central and western parts of the Maya Mountains, while the eastern part of the range has been more eroded. Most of the analyzed river longitudinal profiles (Fig. 14) display an upper reach associated to these low relief surfaces. Here again, the age of this relict landscape is unknown. According to Purdy et al. (2003), uplift in the Maya Mountains did not occur until late Neogene and perhaps no earlier than late Pliocene. The low relief surfaces we observe in the Maya Mountains may have formed during the Middle Miocene as the Mayan paleosurface. In the southern part of the range, the low relief surface of the Maya Mountains gently dip towards the west and seems to connect to the flat topography of the Petén basin.

5.2 Morpho-tectonic interpretations

Landscapes from the Sierra de Chiapas and the Maya Mountains were fragmented and locally rejuvenated by tectonics. We propose to combine our topographic profiles (Figs. 5 and 6), geomorphic maps (Figs. 7 and 8) and analyzed river profiles (Figs. 9 to 14) with published GPS and seismotectonic data in order to locate main active deformation zones. We attempted to define coherent tectonic blocks (Fig. 16) in order to produce a comprehensive map of the plate boundary.

The Tonalá Shear Zone has been depicted as a relict left-lateral structure (Wawrzyniec et al., 2005; Weber et al., 2005). Indeed, it shows no signs of seismic activity (Fig. 3b). However, the differential motion between GPS stations ESPO and CONC (Fig. 16) suggests that the fault zone currently accommodates a $\sim 2.5 \text{ mm yr}^{-1}$ ENE extension. Our geomorphic analyzes suggest that the landscapes of the Chiapas Massif are mostly in steady-state. However, the southern tip of the massif displays evidences of topographic rejuvenation. River profiles crossing the northern segment of

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the Tonalá Shear Zone (profile 6 in Fig. 10) show no major perturbations and indicate thus an equilibrium between erosion and uplift. Towards the SE, river profiles display gentle knickzone associated to a 50–150 m base-level fall (profile 15 in Fig. 15). In the same area, Authemayou et al. (2011) observed that alluvial fans across the fault zone are affected by vertical offsets ranging between 15 and 60 m. The base-level drop we observe in river profiles is thus related to a gentle uplift along the central portion of the Tonalá Shear Zone. Finally, river profiles along the southern termination of the fault zone (profile 21 in Fig. 10) exhibit prominent knickpoints and convex segments which indicate a major disequilibrium. The k_{sn} values increase southward along the Tonalá Shear Zone but in fact all the areas located between the Polochic fault and the Necta fault display high k_{sn} values (Fig. 13). Under constant climate and lithologies, the steepness index (k_{sn}) correlates with uplift rates (e.g., Kirby and Whipple, 2001; Wobus et al., 2006). We suspect thus higher uplift rates along the southern border of the Chiapas Massif (north of the Polochic fault and south of the Necta fault). The Necta fault separates the northern domain, where the topography is almost in steady-state, from the southern domain, where landscapes are being rejuvenated due to an increase in uplift rates. We propose to define a rigid block (referred as “Chiapas Massif sliver” in Fig. 16b) delimited by the Tonalá shear zone to the west, by the La Venta and Tuxtla faults to the east and by the Necta fault to the south. The Tonalá shear zone seems to accommodate a 2.5 mm yr^{-1} extension while the Tuxtla fault instead accommodates a 2.5 mm yr^{-1} shortening (Fig. 16b).

The northern tip of the Central America volcanic arc forms an uplifted plateau with a mean elevation of $\sim 3000 \text{ m}$. The drainage network developed prominent knickzones as it responded to high-amplitude base level changes (Figs. 9 and 10 and k_{sn} map in Fig. 13). The differential motion between GPS stations TPCH and SOL (Fig. 16) indicates a $\sim 5.8 \text{ mm yr}^{-1}$ NNE shortening between the Pacific coastal plain and the Sierra de los Cuchumatanes. We also noted that the motion of GPS stations located along the volcanic arc (MAZ, CHL and SSIA in Fig. 16) is intermediate between the Cocos forearc sliver and the Caribbean plate. From the motion of these GPS stations

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we infer a dextral fault zone bounding the southern edge of the volcanic arc. We suspect that the volcanic arc acts as a tectonic sliver which accommodates a significant part of the motion between the Cocos forearc sliver and the overriding plates. East of the Graben of Guatemala City, the sliver is possibly delimited by two right-lateral fault zones which accommodates each half of the motion ($\sim 13 \text{ mm yr}^{-1}$) between the Cocos forearc sliver and the Caribbean plate. West of the Graben of Guatemala City, the volcanic arc sliver is pinned between the Cocos forearc sliver to the SW, the Polochic sliver to the NE and the Chiapas Massif to the north (Fig. 16b). Though a 6.3 mm yr^{-1} shortening is expected between GPS stations MAZ and JOY, we could not find a clear limit between this volcanic arc sliver and the Motagua sliver.

Within the Sierra Madre de Chiapas orogenic belt, most of the present day seismicity (Fig. 3b) is located along the strike-slip faults of Chiapas, which delimitate the La Venta block (profile 1 in Fig. 5) and the northern part of the Sierra de Chiapas, and along the inner part of the Chiapas fold-and-thrust belt, east of the Sierra de Chiapas and Comitán High uplifted domain. In addition, two historical events were documented within the Central valley of Chiapas: the 14 March 1591 (García-Acosta and Suárez-Reynoso, 1996; Peraldo and Montero, 1999; Guzmán-Speziale, 2010) and the 23 September 1902 (Böse, 1903; Figueroa, 1973) earthquakes. Historical earthquakes of this area were attributed either to the Concordia (Guzmán-Speziale, 2010) or to the Tuxtla (Andreani et al., 2008a) faults. The differential motion between GPS stations CONC and SOLE suggests a $\sim 2.5 \text{ mm yr}^{-1}$ NE-trending compression which is perpendicular to the azimuth of mapped faults. Our geomorphic data suggest that the Tuxtla fault is more likely to have produced these earthquakes. The Concordia fault trace is not associated to any major fault scarps and rivers display a rather low degree of perturbation. By contrast the Tuxtla fault scarp displays a very young and prominent morphology (high hypsometry and low surface roughness) and the drainage network responded to a significant base-level fall ($> 500 \text{ m}$, profiles 1–3 in Fig. 12). Moreover, major topographic uplift took place east of the Tuxtla fault (Comitán High and the Sierra de Chiapas) where the elevation of relict landscapes is between 1600 and 2400 m.

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is mainly absorbed at the boundary of small tectonic blocks which act as “buffers” (Fig. 16b). As a result, significant topographic uplift occurred along two narrow domains. The first one encompasses the Sierra de Chiapas and the western tip of the Polochic sliver (Sierra de los Cuchumatanes) and the second one correspond to the northern tip of the volcanic arc (Fig. 17).

Within the Sierra Madre de Chiapas, the distribution of highest relict landscapes (> 1500 m) indicates that significant topographic uplift occurred between the Tuxtla fault and reverse structures located east of the Sierra de Chiapas and Comitán High. Our results and those of Authemayou et al. (2011) also provide evidences for vertical motions along the Tonalá Shear Zone. There are evidences for a Miocene sinistral motions along the Tonalá Shear Zone and for Tuxtla and Malpaso faults (Guzmán-Speziale and Meneses-Rocha, 2000; Witt et al., 2012b; Molina-Garza et al., 2015). However, the GPS data suggest a present-day $\sim 2.5 \text{ mm yr}^{-1}$ extension along the Tonalá Shear Zone and a similar amount of compression along the Tuxtla fault (Fig. 16). These two opposite movements are possibly related to a counterclockwise rotation of the Chiapas Massif (Fig. 17) following a reorganisation of the subduction interface. The Middle Miocene to present evolution of the Sierra Madre de Chiapas is associated to an inland migration of the Chiapanecan volcanic arc (Damon and Montesinos, 1978) resulting from a flattening of the subduction beneath southern Mexico (Manea and Manea, 2006; Manea et al., 2013). This flattening would have resulted an higher coupling along the subduction interface, as suggested by Franco et al. (2012). As a result, the areas west of the Tuxtla fault (which is located along most of the present day volcanic centers) became partially incorporated into the forearc domain. This would explain why significant Plio-Quaternary topographic growth (> 1000 m) mainly occurred east of the Tuxtla fault rather than along the Tonalá Shear Zone.

The compression between the rotating forearc sliver and the North American plate resulted in topographic uplift along the Sierra de los Cuchumatanes and the northern tip of the Central America volcanic arc (Authemayou et al., 2011, this study). In existing models, the westernmost corner of the Caribbean plate is stretched along NE-trending

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normal faults and the counterclockwise rotation of the forearc sliver is associated to a zipping (i.e. a suture zone) between the inferred prolongation of the Jalpatagua and Motagua faults (Authemayou et al., 2011; Franco et al., 2012). However, a suture zone between the Jalpatagua and Motagua faults may not fully explain why the volcanic arc is uplifted, mainly because most of the elevated Volcanic arc plateau is located west of the area where both faults would be zipped. To explain the atypical motions of GPS stations along the volcanic arc and the topographic elevation of the plateau (MAZ, CHL and SSIA in Fig. 16a) we infer a fault zone bounding the western edge of the volcanic arc (Figs. 16 and 17) and along which the volcanic arc plateau is uplifted. The indentation of the volcanic arc to the north possibly resulted in the topographic rejuvenation of the southern Chiapas Massif as well.

The interactions between the Maya Mountains and the rest of the plate boundary are unclear. Our hypothesis is that a part of the compression associated to the uplift of the volcanic arc and the Sierra de Cuchumatanes is transmitted towards the Yucatán platform and the Maya Mountains through the Petén basin. The Petén basin is a surprisingly flat and low area with a mean elevation of ~ 150 m (swath profile 4 in Fig. 5). It contrast greatly with the topography of the Sierra de Chuchumatanes which instead culminates at ~ 3800 m and the scarp of the Ixcán fault is almost 1000 m high (profile 4 in Fig. 5). We suspect that the Petén basin is underlaid by a rigid basement which acts as a rigid crustal block. The extreme topography of the Sierra de Chuchumatanes can be explained by an abutment along this more rigid block. A rigid Petén block would also explain how a residual part of the motion along the triple junction may have been transmitted to the Yucatán peninsula and Maya Mountains. This residual motion may have reactivated NE-trending faults inherited from the Eocene opening of the Yucatán basin (Rosencrantz, 1990; Leroy et al., 2000).

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6 Conclusions

We demonstrate that a geomorphic analysis allows to classify zones of similar relief patterns that we assume witnessed different tectonic and erosive histories. Using DEM-based geomorphic indices, we examined the topography of the Sierra Madre de Chiapas and the Maya Mountains. We used topographic profiles and morphometric maps in order to understand the spatial distribution of landscapes and we also analyzed in detail the disequilibrium of drainage network in order to map potential vertical displacements. Finally, we combined our results with existing GPS and seismological data in order to better understand the interactions between tectonics and landscapes within the highly diffuse North American–Caribbean–Cocos plate boundary.

Our analysis indicates that the topography of the Sierra Madre de Chiapas and the Maya Mountains is in transient stage. Topographic profiles and morphometric maps highlight elevated relict landscapes which are characterized by a low amplitude relief. These relict landscapes are surrounded by areas being actively eroded. River longitudinal profiles display knickzones which separate an upper reach associated to these relict landscapes from lower and steeper segments along which channels adjust to new base-level conditions. The relict landscapes from the Sierra Madre de Chiapas and the Maya Mountains probably evolved from an initially low topography which was then uplifted and fragmented by tectonics. This initial low relief topography is possibly a northern equivalent of the so-called “Mayan paleosurface” (Authemayou et al., 2011; Brocard et al., 2011) which covered most of the Polochic-Motagua siver and formed at low elevation during the Middle Miocene (between 13 and 7 Ma).

East of 91° W the dynamic of the triple junction is mainly related to the eastward escape of the Caribbean plate (Lyon-Caen et al., 2006; Authemayou et al., 2011), which resulted in sinistral shear along the Polochic and Motagua slivers, dextral shear along the Jalpatagua fault and extension mainly concentrated along the grabens of Guatemala City and Ipala. West of 91° W we mainly observe compression resulting from the counterclockwise rotation of the Cocos forearc siver. Within the Sierra Madre

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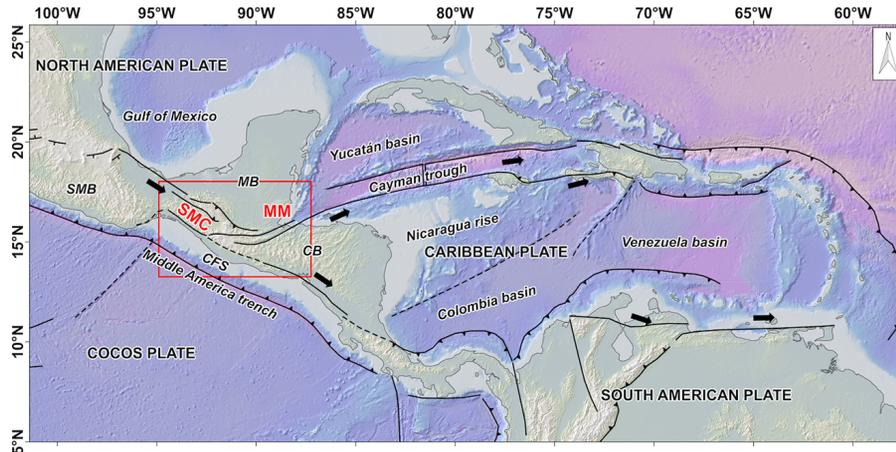


Figure 1. Main plate boundaries in Central America (black lines) and location of the Sierra Madre de Chiapas (SMC) and Maya Mountains (MM) in red. The red box shows the extend of Fig. 2. Abbreviations: CB – Chortis block, CFS – Central America forearc sliver, MB – Maya block, SMB – Southern Mexico block. Topography and bathymetry from the General Bathymetric Chart of the Oceans (GEBCO, <http://www.gebco.net/>).

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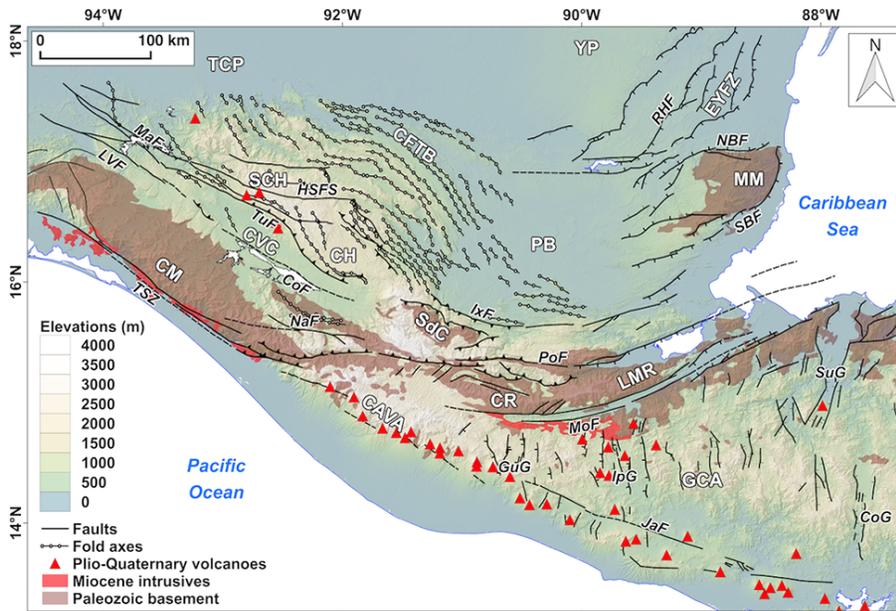


Figure 2. Tectonic map of northern Central America. Structures compiled from Guzmán-Speziale (2001); Meneses-Rocha (2001); Rogers et al. (2002); Purdy et al. (2003); Ratschbacher et al. (2009); Authemayou et al. (2011) and Witt et al. (2012b). Morpho-tectonic domains: CAVA – Central America volcanic arc, CFTB – Chiapas fold-and-thrust belt, CH – Comitán High, CM – Chiapas Massif, CR – Chuacús range, CVC – Central Valley of Chiapas, EYFZ – East Yucatán fault zone, GCA – Grabens of Central America, LMR – Las Minas range, MM – Maya Mountains, PB – Petén basin, SCH – Sierra de Chiapas, SdC – Sierra de los Cuchumatanes, TCP – Tabasco coastal plain, YP – Yucatán platform. Main structures: CoF – Concordia fault, CoG – Comayagua graben, GuG – Guatemala City graben, HSFS – High Sierra fault system, IpG – Ipala graben, LxG – Ixcán fault, JaF – Jalpatagua fault, LVF – La Venta fault, MaF – Malpasó Fault, MoF – Motagua fault, NaF – Nectá fault, NBF – Northern boundary fault, PoF – Polochic fault, RHF – Río Hondo fault, SBF – Southern boundary fault, SuG – Sula graben, TSZ – Tonalá shear zone, TuF – Tuxtla fault.

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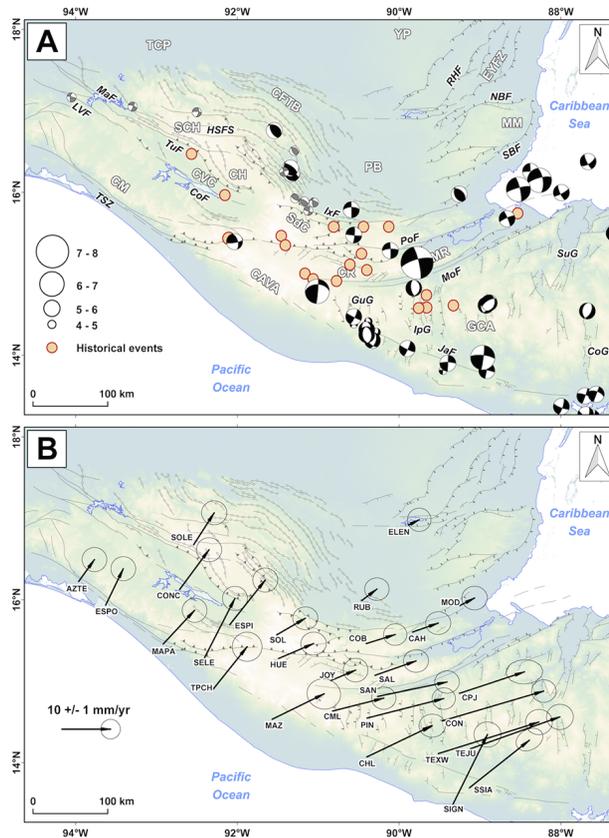


Figure 3. Superficial (depth < 40 km) seismicity in northern Central America **(a)** and GPS velocities with respect to the fixed North American plate **(b)**. Focal mechanisms from Guzmán-Speziale et al. (1989); Guzmán-Speziale (2010) (in greys) and Global CMT Catalog (in black, <http://www.globalcmt.org>). Historical earthquakes (red circles) from White (1984); Singh et al. (1984) and Guzmán-Speziale (2010). GPS velocities are from Franco et al. (2012). See Fig. 2 for abbreviations.

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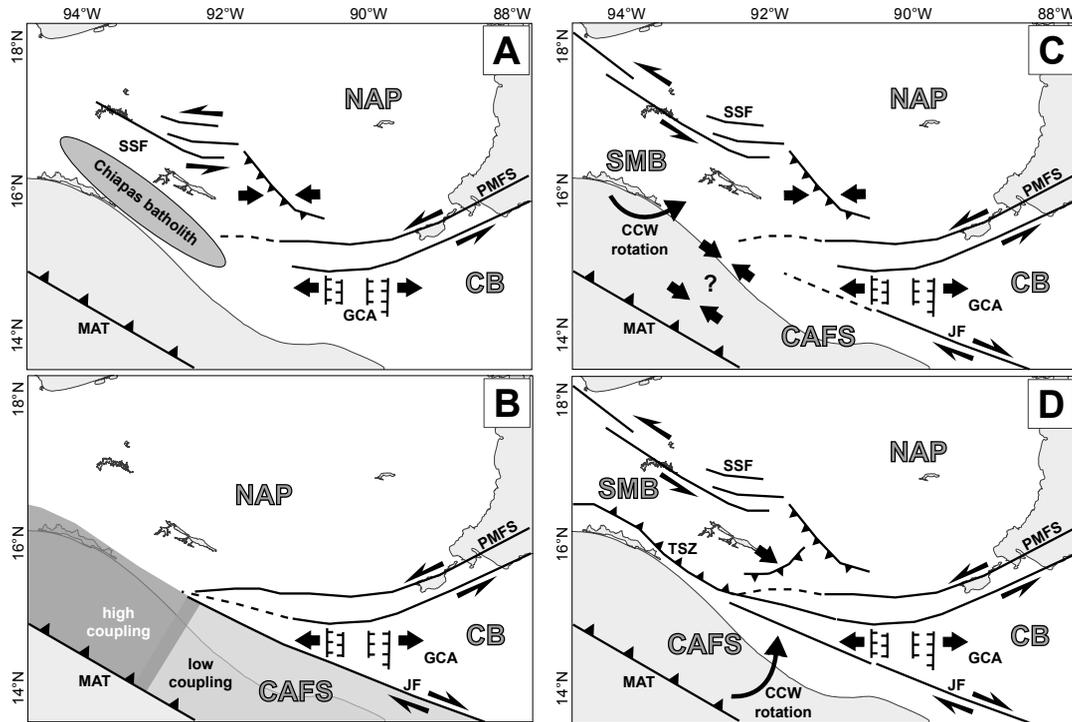


Figure 4. Recent models for the North American–Caribbean–Cocos plate boundary in northern Central America. **(a)** “fault-jog” model from Guzmán-Speziale and Meneses-Rocha (2000) and Guzmán-Speziale (2001). **(b)** model from Lyon-Caen et al. (2006) and Franco et al. (2012). **(c)** model from Andreani et al. (2008a). **(d)** “zipper” model from Authemayou et al. (2011). Main plates and blocks: CAFS – Central America forearc sliver, CB – Chortis block (part of the Caribbean plate), NAP – North American plate, SMB – Southern Mexico block. Main structures: JF – Jalpatagua fault, GCA – grabens of Central America, MAT – Middle America trench, PMFS – Polochic-Motagua fault system, SSF – strike-slip faults of Chiapas, TSZ – Tonalá shear zone.

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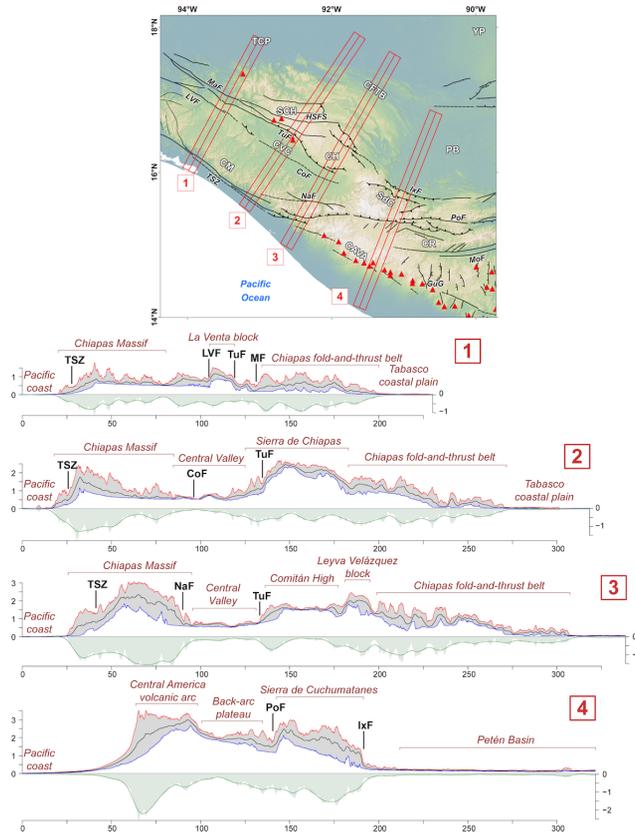


Figure 5. Swath topographic profiles. Swath width is 20 km. Distances and elevations are in km. Vertical exaggeration 10. Red, black and blue curves represent the maximum, mean and minimum elevations, respectively. Green line represent the local incision (subtraction of minimum and maximum elevations). See Fig. 2 for abbreviations.

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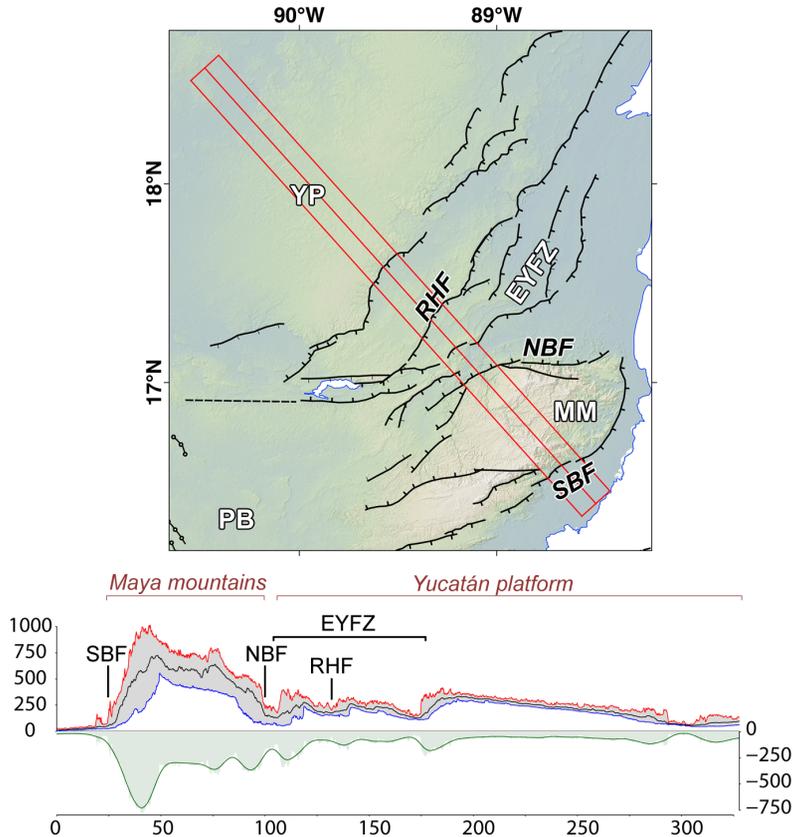


Figure 6. Swath topographic profile across the Maya Mountains and the Yucatán platform. Swath width is 20 km. Distance and elevations are in km. Vertical exaggeration is 20. Red, black and blue curves represent the maximum, mean and minimum elevations, respectively. Green line represent the local incision (subtraction of minimum and maximum elevations). See Fig. 2 for abbreviations.

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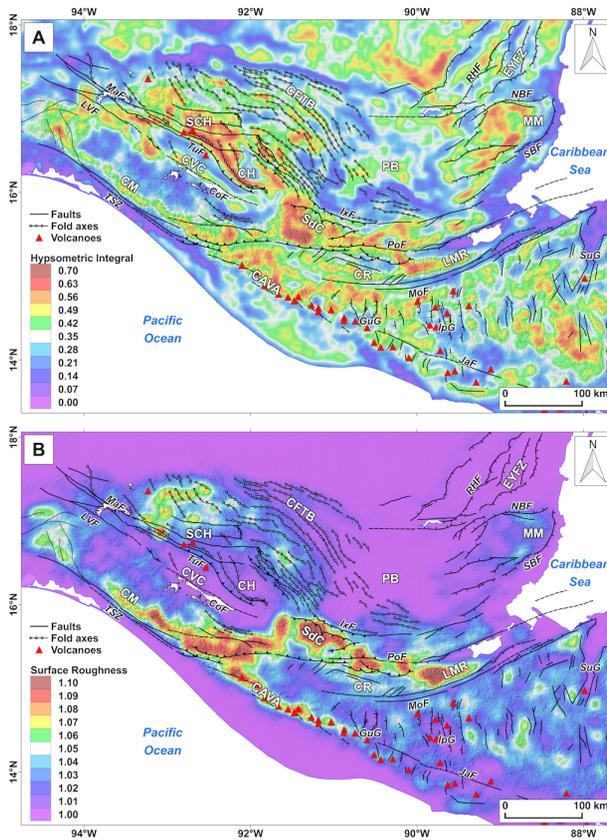


Figure 7. Hypsometric integral (a) and surface roughness (b) for northern Central America. See Fig. 2 for abbreviations.

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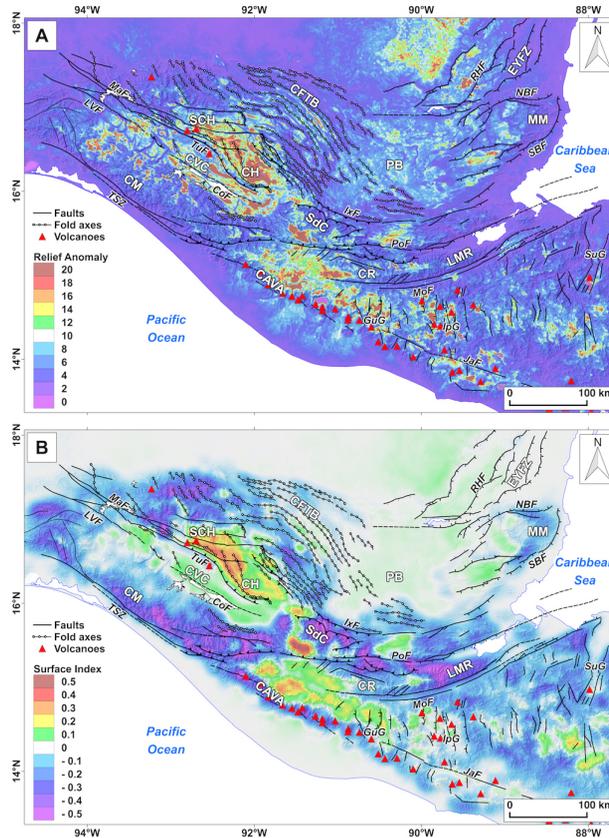


Figure 8. Relief anomaly (a) and surface index (b) for northern Central America. See Fig. 2 for abbreviations.

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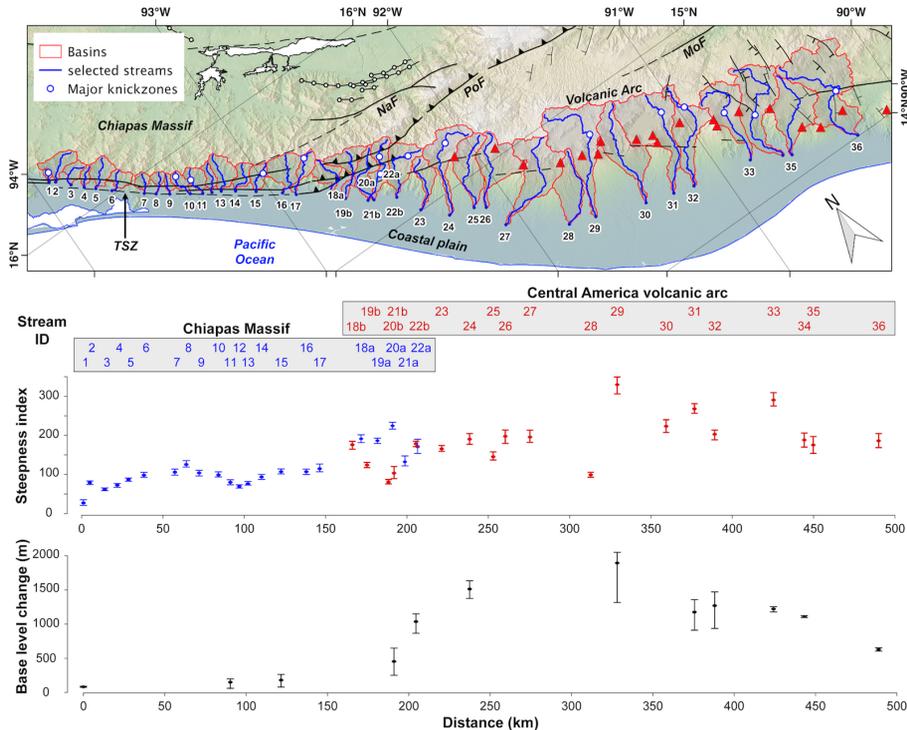


Figure 9. Analyzed streams in Chiapas Massif and Central America volcanic arc. Top: location map. Blue lines represent channels extracted from the modeled drainage network. White dots represent major knickzones. Red lines show limits of catchments. Black lines and red triangles represent main faults and active volcanoes, respectively. Bottom: plot of steepness index (k_{sn}) values and estimated base-level changes along a profile passing through the outlet of each catchment. Abbreviations: MoF – Motagua fault. NaF – Nectia fault. PoF – Polochic fault. TSZ – Tonalá shear zone.

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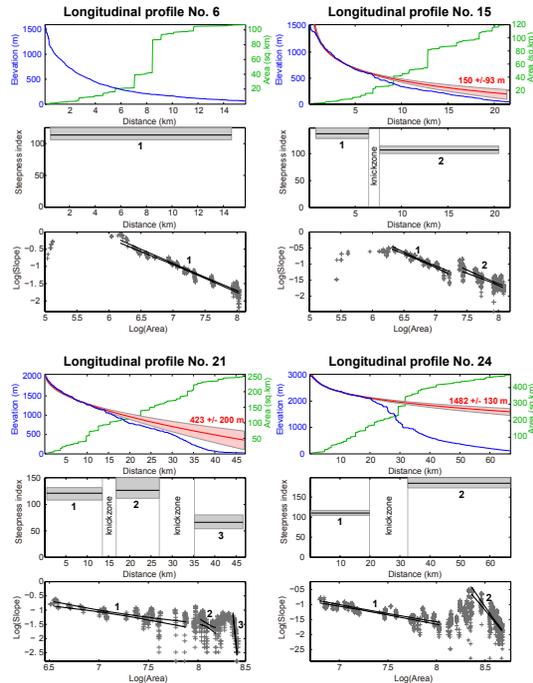


Figure 10. Examples of stream profiles extracted from the modeled drainage network in Chiapas Massif and volcanic arc. Upper plots: blue lines represent longitudinal profiles, green lines show the contributing area (flow accumulation), red lines show reconstructed profiles (interpolation of the slope-distance relation from segments above the upper knickzones, see Eq. 7) and pink polygons represent the uncertainties (based on a bootstrapping method). Central plots: black lines represent extracted stepness index (k_{sn}) values for a given segment and grey polygons show the uncertainties (based on a bootstrapping method). Lower plots: logarithmic plots of slope vs area (grey crosses) and envelopes of regressions (black lines) used to estimate the k_{sn} values.

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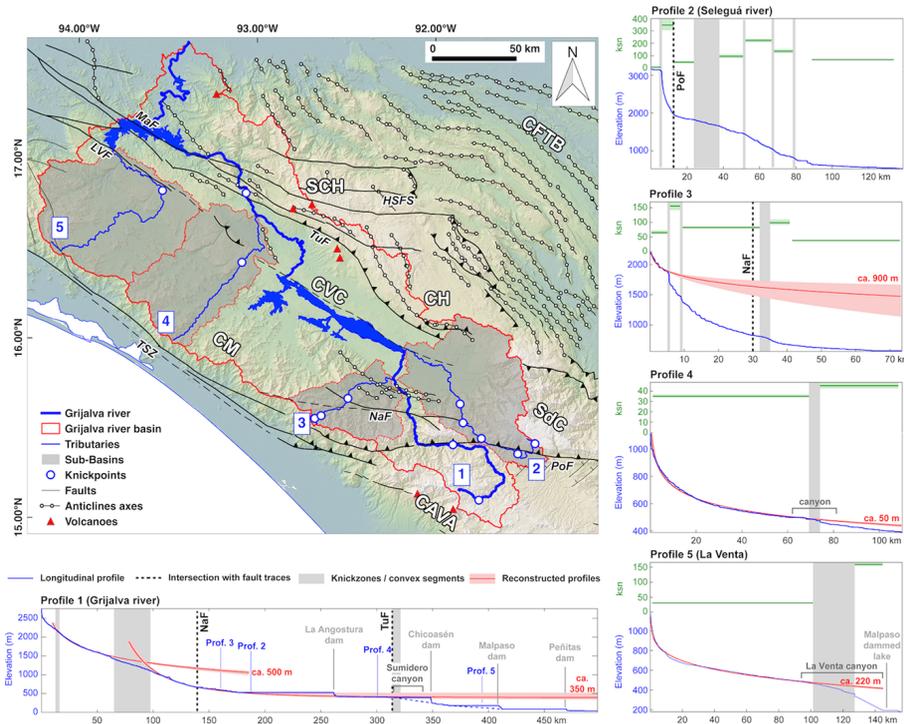


Figure 11. Longitudinal profiles for the Grijalva river and the tributaries from the Sierra de los Cuchumatanes and Chiapas Massif. Profiles were extracted from the modeled drainage network. See Fig. 2 for faults abbreviations.

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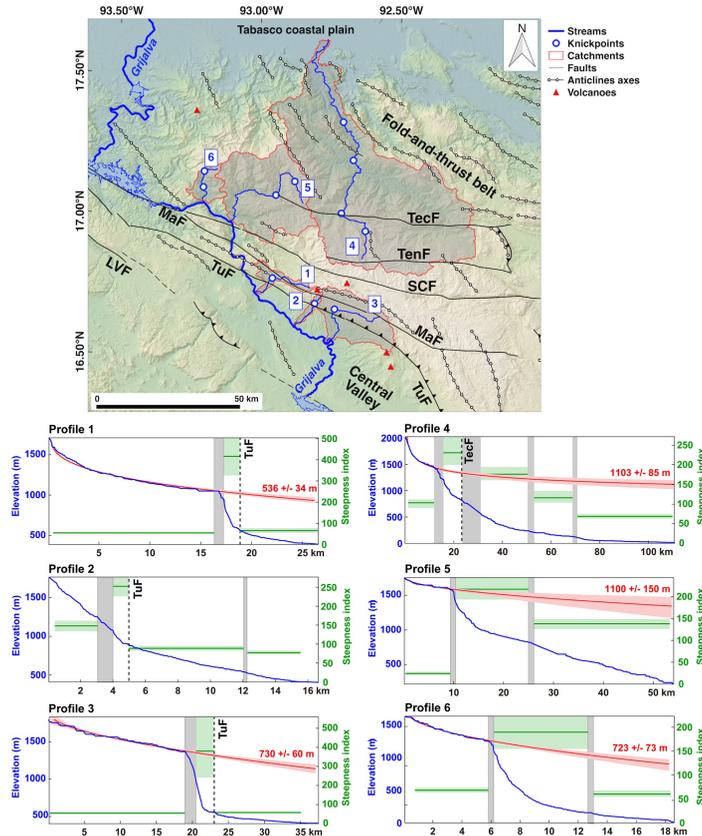


Figure 12. Longitudinal profiles for the Sierra de Chiapas. Channels and profiles were extracted from the modeled drainage network. Abbreviations: LVF – La Venta fault, MaF – Malpasos Fault, SCF – San Cristobal fault, TecF – Tectapan fault, TenF – Tenejapa fault, TuF – Tuxtla fault.

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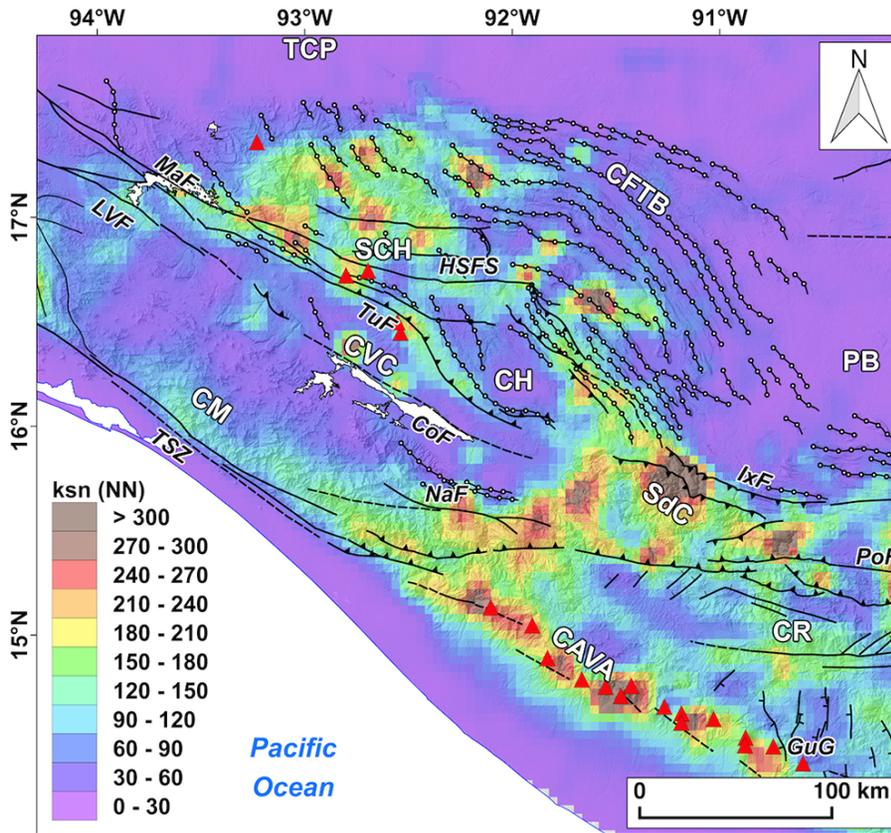


Figure 13. Interpolated map of steepness index (k_{sn}) for the Sierra Madre de Chiapas and the northern segment of the Central America volcanic arc. Values were extracted from river longitudinal profiles using 5 km long segments and interpolated using a natural neighbor (NN) method. See Fig. 2 for abbreviations.

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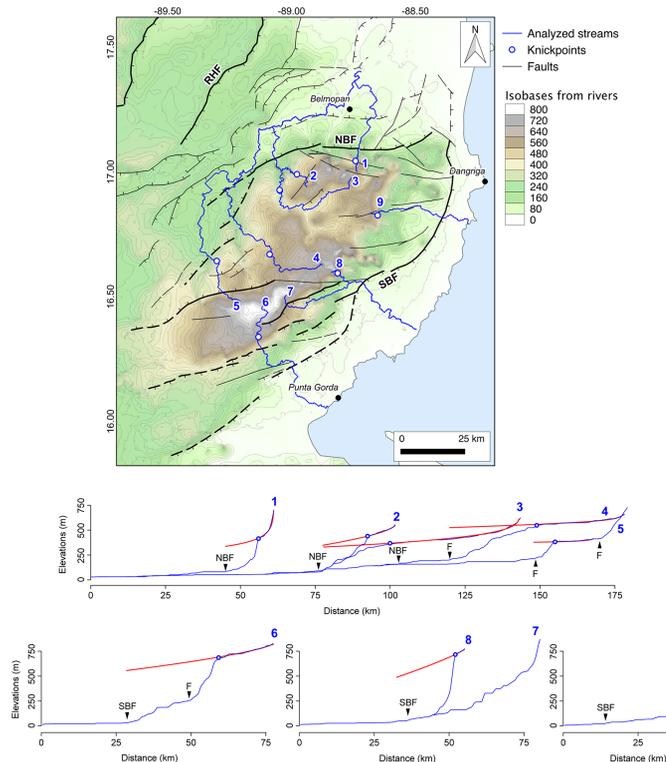


Figure 14. Analysis of drainage network for the Maya Mountains. Top: map of isobases (i.e., interpolated elevations) from rivers with a Strahler order ≥ 2 . Main faults (black lines), analyzed streams (blue lines) and main knickpoints (blue dots) are also reported. Bottom: longitudinal stream profiles. Blue dots are main knickpoints (location on the map). Red lines show profiles reconstructed using segments located above the knickpoints (see Eq. 7). Black arrows show the intersection with main faults. Abbreviations: NBF – Northern Boundary fault, SBF – Southern Boundary fault, RHF – Rio Hondo fault, F – other faults.

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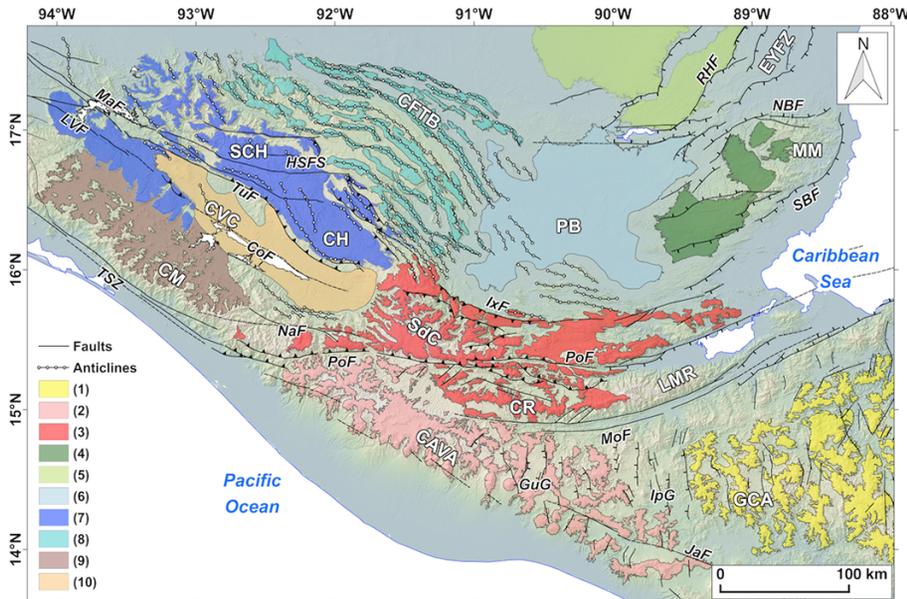


Figure 15. Proposed extension of elevated surfaces and relict landscapes in northern Central America (interpretative map based on morphometric maps, Figs. 7 and 8). Legend: 1 – Remnants of the Miocene ignimbritic plateau (Rogers et al., 2002), 2 – Plio-Quaternary volcanic arc plateau, 3 – Middle Miocene Mayan paleosurface (Authemayou et al., 2011; Brocard et al., 2011), 4 – relict landscape of the Maya Mountains, 5 – tilted surfaces of the Yucatán platform, 6 – Petén basin, 7 – elevated plateaus of La Venta and northern Sierra Madre de Chiapas, 8 – inferred extension of the plateau within the fold-and-thrust belt, 9 – monadnock landscape developed over the Chiapas batholith, 10 – Central valley of Chiapas. See Fig. 2 for faults and morpho-tectonic domains abbreviations.

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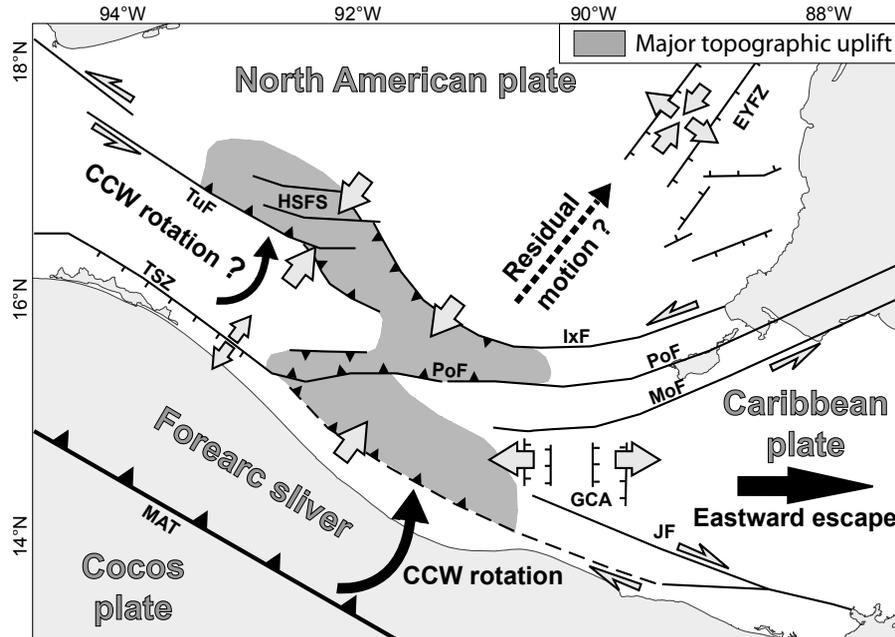


Figure 17. Proposed model for the North American–Caribbean–Cocos plate boundary in northern Central America. See Fig. 2 for faults abbreviations.

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