A geodynamical perspective on the subduction of Cocos and Rivera plates beneath Mexico and Central America

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A geodynamical perspective on the subduction of Cocos and Rivera plates beneath Mexico and Central America

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A B S T R A C T

The Middle America subduction zone (MASZ) is one of the world' most complex convergent margins as it involves the subduction of the Rivera and Cocos young oceanic plates beneath the North American and Caribbean plates and is bounded by the Gulf of California rift and the Panama slab window. Characterized by contorted and unusual slab geometry, irregularly distributed seismicity and volcanism, exceptionally large slow slip events (SSE) and non-volcanic tremors (NVT), this subduction system represents a great natural laboratory for better understanding geodynamic processes at a fundamental level. Based on a solid observational foundation, and incorporating the latest experimental results into a coherent geodynamical framework, we shed light on the main processes controlling the subduction system evolution in this region. The tectonics, volcanism, slab geometry and segmentation along the margin are reviewed from a geodynamical perspective. We proposed and discussed a series of evolutionary scenarios for the Mexican and Central American subduction zones, providing a coherent starting base for future geodynamical modeling studies tailored to this active margin. We discuss comparatively the recently discovered SSEs and NVTs along the MASZ, and try to differentiate among the proposed mechanisms responsible for these observations. Finally we discuss the recent seismic anisotropy observations in a geodynamic context, offering an integrated view of mantle flow pattern along the entire active margin. Although the MASZ as a whole may be considered a fairly complicated region with many unusual features and sometimes controversial interpretations, its complexity and unusual characteristics can improve our knowledge about the linkage between deep and surface processes associated with subduction zone dynamics.

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1. Introduction

As most of the world's devastating earthquakes occur along active subduction zones, understanding the complex interaction between the subducting and overriding plates represents a key element in the long quest of deciphering convergent margin dynamics. The Middle America subduction zone (MASZ) is probably one of the most complex convergent margins on Earth. Along the Middle America Trench (MAT), the Rivera and Cocos Plates subduct beneath the North American and Caribbean Plates, causing irregularly distributed seismicity, slow slip events, and non-volcanic tremors (Kostoglodov et al., 2003; Pardo and Suárez, 1995; Payero et al., 2008). The slab geometry varies significantly along strike and the upper plate volcanism is discontinuous and shows a strong chemical heterogeneity (Carr et al., 2003; Ferrari et al., 2012). Such a diverse subduction system represents a perfect natural laboratory for better understanding geodynamic processes at a fundamental level, and this is precisely the main topic of this paper.

In a general sense, a subduction system consists of several interconnected parts. In fact the subducting slab and the overriding plate are coupled together through the mantle wedge and the upper mantle. When analyzed from a geodynamical standpoint, this complex system acts as a tightly coupled structure where each part of the system affects the components to which it is tied. For example, one of the key characteristics in the evolution of a subduction zone is the nature and thickness of the overriding plate. In fact, different types of overriding plates may produce very different subduction styles. For instance, it has been demonstrated that the slab geometry may significantly change in presence of an over thickened, craton-like, continental upper plate (Lallemand et al., 2005; Manea et al., 2012; Pérez-Gussinyé et al., 2008), inducing a shallow or flat subduction that is not observed when the overriding plate is an oceanic lithosphere. A relatively unique case when a single oceanic plate subducts beneath both types of overriding plates is the Cocos plate, which is currently subducting beneath a continental plate in Mexico, Guatemala, Honduras, and San Salvador, and beneath an oceanic plate in part of Nicaragua and Costa Rica. Apparently, this first order variations in the nature of the overriding plate, strongly influence the Cocos slab geometry and dynamics along the MAT. However, we are currently only in the early stage in the understanding how subducting slabs respond to these controlling factors, and in this paper we want to highlight the importance of first order 3D variations of subduction zones using the Middle America Subduction Zone (MASZ) as an example.

In the last decades a wealth of geophysical observations on many aspects of the MASZ have been collected through various experiments, and many papers have focused on describing associated geodynamics processes at local scale (Arroyo et al., 2009; Dinc et al., 2011; Dzierma et al., 2011; Jödicke et al., 2006; León-Soto et al., 2009; Pérez-Campos et al., 2008; Song et al., 2009; Syracuse et al., 2008; V.C. Manea and M. Manea, 2011; Yang et al., 2009). Observational advances along MASZ continue to reveal diversity in the seismic signals associated with the ongoing subduction of the Cocos slab. A particularly rich example is the shape of the subducting Cocos and Rivera plates along MAT as revealed by several recent seismic experiments. Among these experiments are the Mapping the Rivera Subduction zone seismic experiment (MARS) that imaged a complex geometry of the junction between Rivera and Cocos slabs (Yang et al., 2009); the Middle America Seismic Experiment (MASE) and the Veracruz–Oaxaca seismic line that imaged in great detail the 2D geometry and nature of the subducted Cocos plate beneath Central Mexico and the Tehuantepec Isthmus (Melgar and Pérez-Campos, 2011; Pérez-Campos et al., 2008); the Tomography Under Costa Rica and Nicaragua (TUCAN) experiment as well as other temporary seismic networks, which offered a detailed view into the Central American subduction zone geometry and structure (Arroyo et al., 2009; Dinc et al., 2010, 2011; Syracuse et al., 2008). All these experiments provided for the first time a clear picture of the subducting system beneath Mexico and Central America, offering a solid base for further investigations and interpretations of other subduction related processes as, for example, episodes of slow slip events (SSE) and deep non-volcanic tremors (NVT) (Kostoglodov et al., 2003; Larson et al., 2007; Payero et al., 2008). These events have much longer source durations than regular earthquakes, and are commonly located in the vicinity of the seismogenic zone where regular earthquakes occur. As oceanic lithosphere descends beneath the overriding plate the contact between the two plates undergoes significant transformations in response to the increasing pressure and temperature with depth. The geometry of the subducted Cocos plate changes from perfectly flat slab beneath Central Mexico to steep slab beneath Costa Rica. In both regions SSE and NVT have been recorded in the transition zone from fully locked on the shallow, updip side, to stable sliding downdip part of the slab interface, where the oceanic plate descends freely into the hotter surrounding mantle. But how this transition zone works is not yet understood. Such a dramatic change in plate geometry significantly influences the location and magnitude of recorded SSE. While in the Northern Costa Rica seismogenic zone slow slips occur at the updip transition from stick–slip to stable sliding and have relatively small surface displacements (1–2 cm) (Dragert et al., 2001), in Central Mexico SSE are mostly located along the flat slab interface and induce surface displacements almost one order of magnitude larger (~10 cm) (Kostoglodov et al., 2003; Larson et al., 2007). It is possible that the P–T conditions along these two slab interfaces may be so significantly different to the extent of inducing end member SSEs. If this is the case a comparative study of the Cocos slab thermal structure in both regions has a great potential to give insights into the current models for the origin of SSE and NVT. Identifying P–T conditions farther down the slab interface are also essential, because hydration of the mantle wedge favor mantle melting and therefore control the location of volcanic arcs. Whereas in Central America the active volcanic front is parallel to MAT and approaches the global average depth above the slab of 105 km (Dinc et al., 2011; Syracuse and Abers, 2006) in Mexico large along-strike variations of the dip of the subducting Cocos plate produce a rather peculiar space distribution of the volcanic arc, with the volcanic front not parallel to the trench and volcanism sometimes located at over 200 km above the slab interface. Although the MASZ as a whole may be considered a fairly complicated region with many unusual features and sometimes controversial interpretations, its complexity and unusual characteristics also provide a rare opportunity to carve deep inside a subducting zone and bring to the surface something novel and worthy of note for future large-scale subduction experiments.

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In this paper we present an overview the main geological and geophysical observations along the Mexican and Central America subduction zones, and we analyze them in an integrated–comparative approach. New observations and geodynamic models, that shed light on processes controlling the subduction system evolution of this region, supplement this overview. Considering that many existing observations along the MASZ are not adequately explained in a single, coherent geodynamic framework, in this paper we attempt to tie together the available dots of information gathered in various individual study areas, offering an integrated view of first-order geodynamic processes resulting from the interaction between the subducting Rivera and Cocos slabs and the North America and Caribbean plates.

2. Tectonic settings

The tectonic environment of the subduction of the Rivera and Cocos plates beneath the North America and Caribbean plates offers an accessible natural laboratory for the study of how plate tectonics works in different contrasting tectonic settings. Some factor that makes this region favorable for an integrated geodynamic study is that many outputs of the subduction system are accessible for study onshore, a number of oceanic input parameters, like plate age, convergence rates, plate morphology and structure, are reasonably well constrained, and that recent geophysical experiments start revealing the other aspects of the subduction system at a level of detail never seen before.

2.1. Oceanic domain

Both oceanic plates, Rivera and Cocos, are remnants of the large Farallon plate that gradually fragmented into a series of smaller plates since ~30–28 Ma when the East Pacific Rise (EPR) start interacting with the North American Plate (Atwater and Stock, 1998). The initial contact between the EPR and the trench offshore southern California resulted in the separation of the Juan de Fuca plate to the north of the Mendocino triple junction. The Cocos plate was formed at ~23 Ma when the Farallon plate broke in two at an equatorial latitude leaving the Nazca plate to the south (Lonsdale, 2005). As the Cocos–Pacific–North America triple junction (the Rivera TJ) moved to the south the northern part of the Cocos plate broke into several smaller plates that did not subduct completely and become part of the Pacific plate when the Pacific–North America plate boundary localized in the Gulf of California (Monterey, Arguello, Guadalupe and Magdalena microplates) (Lonsdale, 1991). The Rivera plate was the last fragment to be lost by the Cocos plate, which starts to act as an independent microplate since at least 10 Ma (DeMets and Traylen, 2000). The Rivera plate presently subducts beneath North America at the northern end of the MAT and accretes seafloor along its western boundary, the Pacific–Rivera spreading center, which represent the northern termination of the EPR. This small plate, bounded by the Rivera fracture zone, the EPR, the Tamayo fracture zone and the MAT (Fig. 1), consists of two distinct morphotectonic units: a wide region of mostly undisturbed oceanic crust and a structurally complex zone at its southeastern tip formed as a result of rift propagation and convergence between the Rivera and Cocos plates with the El Gordo graben (EGG) extensional zone in proximity to the trench (Bandy et al., 1995). The larger Cocos plate is bounded to the northeast by the North American plate and the Caribbean plate, on the west by the Pacific plate and to the south by the Nazca plate (Fig. 1). Both Rivera and Cocos plates, are relatively young (10–25 Ma) oceanic plates that subduct along the Middle America Trench (MAT) at variable convergence rates (~30 mm/yr for Rivera and 50 to 90 mm/yr for Cocos) (DeMets, 2001; DeMets and Traylen, 2000). The convergence rate between the Cocos and the North America or Caribbean plates increases progressively to the southeast along the MAT, from ~5 cm/yr off central Mexico to ~9 cm/yr off southern Costa Rica (DeMets, 2001). The age of the plate subducting at the MAT gradually increase from ~10 Ma off western Mexico, to ~15 Ma off central Mexico, to ~25 Ma off Guatemala, El Salvador and Nicaragua, to eventually decrease to ~15 Ma off southeast Costa Rica (Fig. 1).

Despite the relative continuous variation of subduction parameters along the MAT, several main tectonic structures affect the Cocos plate along the trench. The limit between the Rivera and Cocos plate along the MAT is marked by the El Gordo graben (EGG) that has been proposed to mark the southwest tip of an active extension zone between the two plates (Bandy et al., 2000). To the south of EGG a series of well-defined fracture zones mark the surface of the Cocos plate. The most important of these features are the Orozco, O'Gorman and Tehuantepec fracture zones (Fig. 1). The Orozco fracture zone was created by the physical extension of the Clarion transform fault that offset spreading centers along the EPR and it was probably part of an early border between the Rivera and Cocos plates (Mammerickx and Klitgord, 1982). Recent seismic studies using data recorded during the MARS experiment suggests that the subducted Cocos slab could be currently fragmenting along the Orozco fracture zone because of the stress imposed by different slab dip on each side of this structure (Dougherty et al., 2012; Stubailo et al., 2012). On the other hand, the O'Gorman fracture zone is the remnant of a small offset of spreading segments of the short living Mathematician ridge (Mammerickx and Klitgord, 1982). It defines a distinctive seismic transition at the Oaxaca–Guerrero seismogenic zone in Central Mexico and it is assumed to be a natural physical boundary along the Mexico subduction zone (Kostoglodov and Ponce, 1994; Singh and Mortera, 1991). However, no significant age offsets is observed across the O'Gorman fracture zone at the MAT (Kanjorsky, 2003). Located farther southeast the Tehuantepec ridge is a major transpressional structure formed along a former transform fault at 15–20 Ma. This major structure is characterized by a low-density and highly magnetic rock body just beneath the oceanic crust, which is interpreted as a partially serpentinized root (Manea et al., 2003, 2005). The ridge separates the oceanic lithosphere into two distinct tectonic regions with an age offset of ~10 Ma (Manea et al., 2003, 2005; McMillen et al., 1982). The main morphologic feature of the southern part of the Cocos plate is the Cocos Ridge, which is a prominent submarine aseismic ridge currently subducting off Costa Rica and Panama, almost orthogonally to the strike of the MAT. The ridge stands ~2 km above the surrounding seafloor and sits on top of oceanic crust that exceeds 20 km in thickness (Walther, 2003). Interpreted to be the trace of the Galápagos hotspot since ~20–22 Ma (Barckhausen et al., 2001; Hey, 1977; Lonsdale and Klitgord, 1978), the indentation of the Cocos Ridge into the Caribbean plate leads to significant uplift and exhumation of deep crustal rocks (Gardner et al., 1992; Gräfe, 1998; Gräfe et al., 1997; Meschede et al., 1999) and induces and arc-parallel tectonic escapes of a fore-arc sliver (LaFemina et al., 2009). The boundary between the Cocos and Nazca Plates near the MAT is the Panama fracture zone. This is a right-lateral active transform fault intersecting the MAT near the Costa Rica–Panama border whose subduction produced a slab window that expands in a north–south direction, and shifts to the northeast (Abratis and Wörner, 2001; Johnston and Thorkelson, 1997).

Apart of grabens, fracture zones and ridges, the Cocos plate morphology is characterized by abundant seamounts that roughen the crust in different locations. Offshore Mexico, in the vicinity of O'Gorman fracture zone, several parallel ridges composed of small to medium sized volcanic cones of seamounts are entering the subduction zone and remain physically intact throughout the subduction process (Kanjorsky, 2003). Interestingly, these seamount chains have associated a series of new normal faults parallel to MAT. They tend to form adjacent to the seamount lineaments along their flexural moats. Compared with the smoother oceanic plate surface to the north, this roughed and faulted region shows an increase in small-magnitude earthquakes associated with the seamounts (Kanjorsky, 2003). A smooth-rough transition in bathymetry of the oceanic plate can also be observed offshore

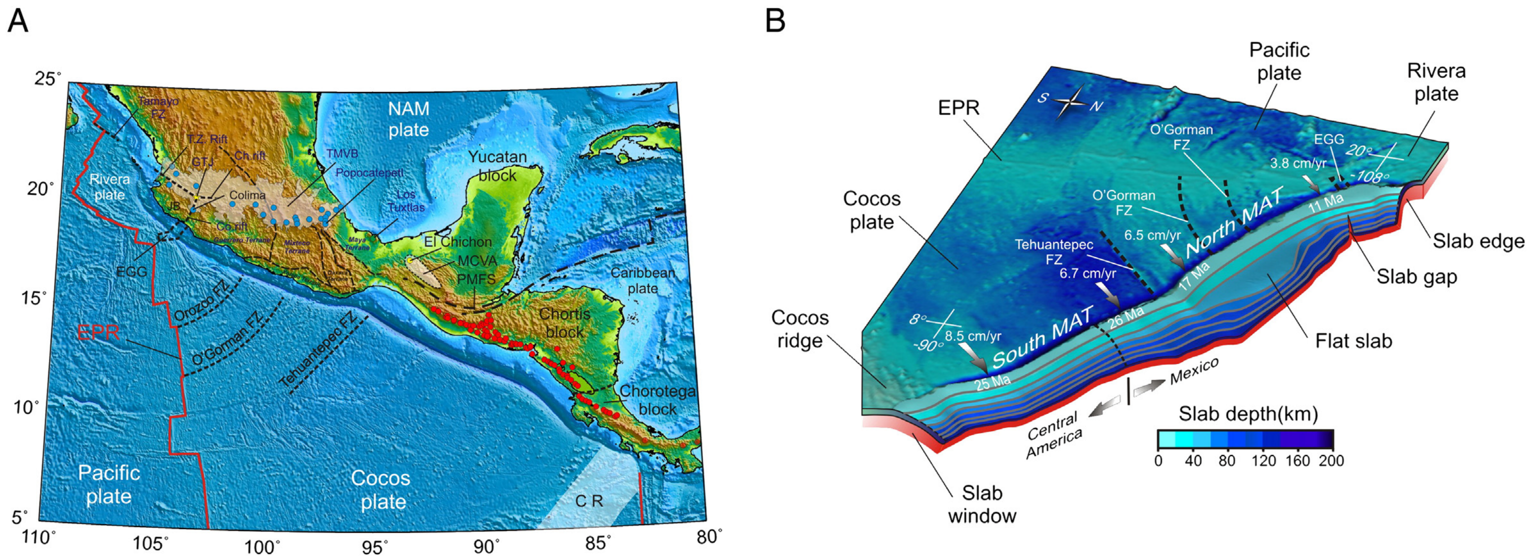

Fig. 1. A. Geodynamic and tectonic setting along Middle America Subduction Zone. JB: Jalisco Block; Ch. Rift—Chapala rift; Co. rift—Colima rift; EGG—El Gordo Graben; EPR: East Pacific Rise; MCVA: Modern Chiapanecan Volcanic Arc; PMFS: Polochic–Motagua Fault System; CR—Cocos Ridge. The main Quaternary volcanic centers of the Trans Mexican Volcanic Belt (TMVB) and the Central American Volcanic Arc (CAVA) are shown as blue and red dots, respectively. B. 3-D view of the Pacific, Rivera and Cocos plates' bathymetry with geometry of the subducted slab and contours of the depth to the Wadati–Benioff zone (every 20 km). Grey arrows are vectors of the present plate convergence along the MAT. The red layer beneath the subducting plate represents the sub-slab asthenosphere.

Costa Rica, where the smooth seafloor is formed at the EPR, while the irregular, hotspot-thickened seafloor is created along the Cocos–Nazca spreading center (Ranero and Von Huene, 2000; Sak et al., 2009) (Fig. 1). The entire bathymetry along the MAT shows a fairly complex response of the crust to the subduction process, with the abyssal–hill fault system reactivated due to the plate bending increasing in number and offset where the bending is more pronounced. This active tectonic fabric cuts across the whole oceanic crust into the mantle, favoring hydration of the upper part of the lithosphere (Ranero et al., 2003).

2.2. Continental domain

The North America and Caribbean plates that override the subducting Rivera and Cocos plates are composed by a series of crustal blocks and terranes. In western Mexico, the Rivera plate is currently subducting beneath the western part of the Guerrero terrane, named Jalisco Block, a distinct geological unit whose continental boundaries are being reactivated forming extensional corridors called Tepic–Zacoalco and Colima rifts (Fig. 1) (Allan et al., 1991; Luhr et al., 1985; Rosas-Elguera et al., 1996). To the southwest the Jalisco Block is bounded by the MAT and its long-term interaction with the Rivera plate produced coastal uplift with an average rate of ~3 mm/year during the past 1300 years (Ramírez-Herrera et al., 2004, 2011). At the northeastern corner of the Jalisco block the Tepic–Zacoalco and Colima rifts join with the Citlala rift forming an R–R–R type triple junction, called Guadalajara triple junction (Rosas-Elguera et al., 1997). Recent GPS measurements show that present-day movement of the Jalisco block with respect to the North America plate is ~2 mm/yr toward southwest and the Guadalajara triple junction moves westward at the same rate of ~2 mm/yr (Selvans et al., 2011). The Tepic–Zacoalco rift is composed by different fault systems characterized by left-lateral and then right lateral shear in the Middle to Late Miocene (Ferrari, 1995) but that become essentially extensional since the latest Miocene (Ferrari and Rosas-Elguera, 2000). The northern part of the Tepic–Zacoalco rift appears inactive whereas the southern part shows geologic evidence and geomorphic indicators of recent faulting (Ferrari and Rosas-Elguera, 2000). The seismicity however is discontinuous and moderate in magnitude (Núñez-Cornú et al., 2002; Suarez et al., 1994) probably because of the small rates of extension (<8 mm/yr) across both the Colima and Tepic–Zacoalco rifts (Selvans et al., 2011).

East of the Jalisco block, the North America continental crust is composed by different crustal terranes with different ages and thickness (Fig. 1) (Ferrari et al., 2012; Sedlock et al., 1993). East of the Colima rift the eastern part of the Guerrero terrane consists of a volcano-sedimentary to low-grade metamorphic assemblages of Mesozoic age with a crust thickness not exceeding 35 km. The Guerrero is thrusted onto the Paleozoic metamorphic rocks of the Mixteco terranes, which in turn is sutured with the Precambrian Oaxaca terrane. This Paleozoic and Precambrian terranes constitute the core of continental Mexico where the crust is up to 50 km thick. Bounding to the south the Guerrero, Mixteca and Oaxaca terranes is a trench parallel belt of low- to medium-grade metamorphic and plutonic rocks called Xolapa terrane, which is considered to have formed by the exhumation of the terranes to the north during the Early Tertiary (Herrmann et al., 1994; Ratschbacher et al., 2009). The southeastern limit of the North America plate is constituted by the Maya terrane, formed by a Precambrian to Paleozoic basement with a Mesozoic cover. The easternmost part of the Maya terrane is the Yucatan block, a large fragment of over-thickened continental lithosphere (Shapiro and Ritzwoller, 2003) rifted from cratonic North America during the opening of the Gulf of Mexico. After rotating counterclockwise the Yucatan Block reached its present position during the Early Cretaceous, and suffered almost no movement and internal deformation since then (Pindell, 1985; Pindell and Dewey, 1982; Ross and Scotese, 1988).

The NAM–Caribbean plate boundary consists of a left-lateral strike-slip fault system that due to its southward convex trace has induced significant deformation in a wide area of both plates, such as shortening and transpression to the north of the boundary in Chiapas, and extension and transtension to the south in Guatemala (Authemayou et al., 2011; Burkart and Self, 1985; Gordon and Muehlberger, 1994). The nearly 400 km long fault system is composed of three large, curved, subparallel, left-lateral strike-slip faults: the Polochic, Motagua, and Jocotan–Chamelecón faults. This major transform boundary extends eastward over more than 2000 km, through the Caribbean Sea up to the Puerto-Rico subduction trench (Fig. 1). To the west the connection of this active fault system with the MAT and the COCOS plate remains poorly constrained (Burkart, 1983) and will be reviewed in the chapter "*North America, Cocos and Caribbean plates triple junction*".

South of Motagua–Polochic fault system Central America has been usually divided into two main tectonic blocks: the Chortis Block to the northwest and the Chorotega Block to the southeast. The Chortis Block consists of a continental basement and the accreted oceanic arc rocks of the Siuna Terrane (Rogers et al., 2007) whereas the Chorotega Block lacks a crystalline basement and is composed by a thickened oceanic and arc crust (Buchs et al., 2010; Case et al., 1990; Linkimer et al., 2010). Geologic evidences and paleotectonic reconstructions indicate that at least in the Cretaceous the Chortis Block was part of the NAM plate and was located south of the Guerrero–Oaxaca coast in southern Mexico (Molina-Garza et al., 2012; Pindell and Kennan, 2009; Ratschbacher et al., 2009; Rogers et al., 2007). At the end of Cretaceous the northern part of the Caribbean arc (Siuna arc) collided and sutured to the southeast part of the continental Chortis. Then in the Early Tertiary the block started to move east-southeastward along a complex left lateral shear zone and eventually became part of the Caribbean plate sometimes during the Oligocene (Pindell and Kennan, 2009; Ratschbacher et al., 2009). The western part of the Chortis block is the only true continental crust of the present-day Caribbean plate and is therefore an important element in the subduction dynamics of this region. The Hess escarpment marks the boundary of the Chortis Block with the Caribbean oceanic crust whereas the Santa Elena suture is the boundary with the Chorotega Block (Rogers et al., 2007).

3. The Mexican and Central America volcanic arcs

Subduction of the Cocos and Rivera plates and their common ancestor, the Farallon plate, beneath the North American and Caribbean plates has produced significant intraplate deformation, and a series of volcanic arcs in Mexico and Central America. Although subduction was active since the Permo-Triassic along western Mexico and since Late Cretaceous on the western boundary of the Caribbean plate the present subduction system along the MAT developed only in the Neogene. During the past 20 Ma the MAT subduction system underwent significant changes in terms of slab geometry and the consequence of this dynamics remained imprinted in the configuration and distribution of volcanic arcs.

3.1. The Mexican volcanic arcs

In Mexico the Neogene arc volcanism is discontinuous and represented by the ~1000 km long, Trans-Mexican Volcanic Belt (TMVB) (Ferrari et al., 2012), followed to the southeast by a series of volcanic fields separated by gaps: the submarine Anegada High offshore Veracruz (Ferrari et al., 2005), the Los Tuxtlas Volcanic Field north-northwest the Tehuantepec Isthmus (Nelson et al., 1995), and the modern Chiapanecan volcanic arc (MCVA) (Damon and Montesinos, 1978). The TMVB is one of the most unusual active volcanic arcs; it has a variable width ranging between 90 and 230 km, is not parallel to the MAT, and the main stratovolcanoes are aligned almost orthogonal to the general orientation of the arc. It displays the whole range of volcanic edifices, with large stratovolcanoes, monogenetic cones, shield volcanoes, dome complexes, and major calderas.

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Typical subduction related calc-alkaline rocks volumetrically dominate the composition of volcanism in the TMVB but coexist with smaller volumes of intraplate-like lavas, potassium-rich rocks and adakites (Ferrari et al., 2012; Gómez-Tuena et al., 2007). Adakitic rocks are found at the greatest distance from the trench associated with the Middle Miocene TMVB and along the volcanic front of the central TMVB during the Plio-Quaternary. It has been proposed that the adakitic signature is the result of slab melting, which, in the case of the middle Miocene rocks, was promoted by prolonged flat subduction (Gómez-Tuena et al., 2003; Mori et al., 2007). The prominent Mexican stratovolcanoes characteristic of the modern TMVB were built in the last m.y. In the eastern TMVB the active stratovolcanoes lie at the volcanic front. By contrast in the western TMVB, underlain by the Rivera plate, they are located ~100 km behind the volcanic front, the only exception being the Colima volcanic complex, which is the largest volcanic center of the TMVB (Robin et al., 1987) and the closest to the trench. Another important characteristic of the TMVB is the presence of various monogenetic volcanic fields, such as the Michoacán–Guanajuato and Tenango–Chichinautzin volcanic fields (Mazzarini et al., 2010). Although the aggregated volume of these monogenetic volcanic fields is small, they are distributed over relatively large areas, providing a rare opportunity to study the time-space variation of different geochemical component derived from the subducting slab (Johnson et al., 2009).

In southeastern Mexico, the MCVA is a ~150 km long, NW–SE trending volcanic belt developed since 2.1 Ma (Damon and Montesinos, 1978; Mora et al., 2012). The MCVA is also atypical as it lies well inland at a distance of 300–350 km from the MAT, trends obliquely to the trench, and sits up to ~200 km above the subducting Cocos plate (Manea and Manea, 2008). The best-studied center is the active El Chichón volcano, which lies at the northwestern tip of the MCVA. The El Chichon has an uncommon composition transitional from calc-alkaline to adakitic (De Ignacio et al., 2003; Macías et al., 2003). Its location ~200 km above the subducting Cocos slab has been explained by the strong dehydration of a serpentinized mantle root associated to the subducting Tehuantepec ridge (Manea and Manea, 2008).

3.2. The Central America volcanic arc

Unlike the Mexican volcanic arcs, the Central American volcanic arc (CAVA) runs parallel to the MAT from the Mexico-Guatemalan border to central Costa Rica, where is followed by a gap in volcanic activity from central Costa Rica to Panama. In the upper plate, the CAVA is built upon both the Chorotega and Chortis blocks, with the northwest segment of the arc located on Paleozoic continental crust, while the southeast segment develops on Mesozoic oceanic crust (Alvarado et al., 2007). Another characteristic that contrast with the Mexican arcs is the relatively regular spacing between the volcanic centers (~27 km on average, Carr et al., 2003). Although plate tectonic parameters such as convergence rate, age of the subducting Cocos Plate, thickness and type of subducted sediment, show little variation along MAT in Central America (Kimura et al., 1997), significant compositional variation is recorded along the arc. Volcanic products show the strongest influence of slab-derived fluids in Nicaragua, which decrease toward Guatemala and, especially, toward Costa Rica, where the produced melts show minimal influence of subduction (Carr et al., 1990; Leeman et al., 1994; Patino et al., 2000). Based on the analysis of P-wave velocity, Vp/Vs ratio and local earthquake hypocentres located in south Nicaragua and north Costa Rica, Dinc et al. (2010, 2011) show the existence of a sharp lateral transition between hydrated (2.5 wt.%) and almost non-hydrated mantle within a distance of about just 10 km. Dinc et al. (2011) proposes that this abrupt change can be related with a significant change in the tectonic regime in this area and the larger amplitude of slab roll-back observed in Nicaragua.

Using isotope geochemistry and seismic velocity anisotropy Hoernle et al. (2008) show the existence of trench-parallel flow in the mantle wedge beneath Costa Rica and Nicaragua at a rate of 6.3–19 cm/yr, similarly to other regions in the world where the trench is moving forward or retreating (Hall et al., 2000; Smith et al., 2001).

The observed variations in the geochemical signal recorded in igneous rocks along the CAVA have been attributed to variations in subduction angle, thermal structure and degree of hydration in the forearc bulge (Leeman and Carr, 1995; Rüpke et al., 2002), compositional changes in subducted marine sediments (Patino et al., 2000), and large changes in crustal thickness (Carr et al., 1990; Feigenson and Carr, 1986). Interestingly, large variations in crustal thickness seem to have different effects in Mexico and Central America. While in Mexico they appear to control slab geometry, in Central America they seem to influence the composition of volcanism. Adakitic and intraplate (OIB) lavas are not common along the CAVA, except for rocks in southeastern Costa Rica. In this region, the Panama slab window formed since 8 Ma because of the subduction of the Cocos ridge and the Panama fracture zone (Johnston and Thorkelson, 1997). Adakites are generated by the melting of the oceanic crust at the leading edge of the subducted Cocos slab exposed to the hot, asthenospheric mantle, whereas OIB magmas have been associated to an enriched mantle flowing into the window from the Galapagos hotspot (Abratis and Wörner, 2001; Gazel et al., 2011).

4. Configuration of the subducting Rivera and Cocos slabs

In recent years, several geophysical experiments have revealed in good detail the subduction structure along the MAT. In Mexico, the intraslab seismicity of the young Rivera subducting plate is limited to ~100 km of depth, and previous studies were not able to constrain the shape of the slab farther deep. Using hypocenters of local and teleseismic earthquakes, the pioneering work of Pardo and Suárez (1993) proposed that Rivera had a ~50° dipping slab; however the slab geometry at greater depths, as well as the lateral variations, remained pretty much unknown until recently. The MARS seismic experiment revealed the 3D upper mantle structure down to 400 km of depth beneath the Jalisco block (Yang et al., 2009). The P wave tomographic model imaged two important features: 1) a gap between the Rivera and Cocos slabs that increases in size with depth, and 2) that starting at a depth of ~100 km, both the Rivera and Cocos slabs increase their dip such as the slabs are deeper than 200 km beneath the rear part of the TMVB. In addition, the Rivera slab dips into the mantle more steeply (60–65°) than the adjacent and slightly older Cocos slab. This finding is quite surprising because the subducting Rivera plate is only 10 Myr old at the MAT and the slab should have smaller negative buoyancy and therefore a smaller dip angle. It is unlikely that only one factor could have caused the Rivera slab to dip at ~65° beneath the TMVB, and probably a combination of different factors contributed to this unusual slab geometry. A slowdown in the Rivera–North America convergence rate from 8.5 Ma to 4.6 Ma and then again between 3.6 and 1 Ma (DeMets and Traylen, 2000) combined with a decrease in the viscosity above the slab can reduce considerably the dynamic pressure in the mantle wedge, allowing the slab pull to be the dominant driving force, rather than wedge suction force (Manea and Gurnis, 2007). The mantle wedge viscosity reduction is caused by the toroidal inflow in which hot mantle material located at the Rivera western slab edge and in the proximity of Rivera–Cocos slab gap, moved into the mantle wedge (Ferrari et al., 2001; Schellart, 2004). Actually, the slab dip divergence between the two slabs was initiated before the Rivera plate completely detached from the Cocos plate. The jump toward the trench at ~5 Ma of the EPR segment located near the Rivera plate would have significantly contributed to the vertical tear initiation between the two slabs (Fig. 2). In this setting, the subducting Rivera slab probably lost part of the lateral drag force from the Cocos slab ~5 Myr ago and, as a consequence, the convergence rate diminished.

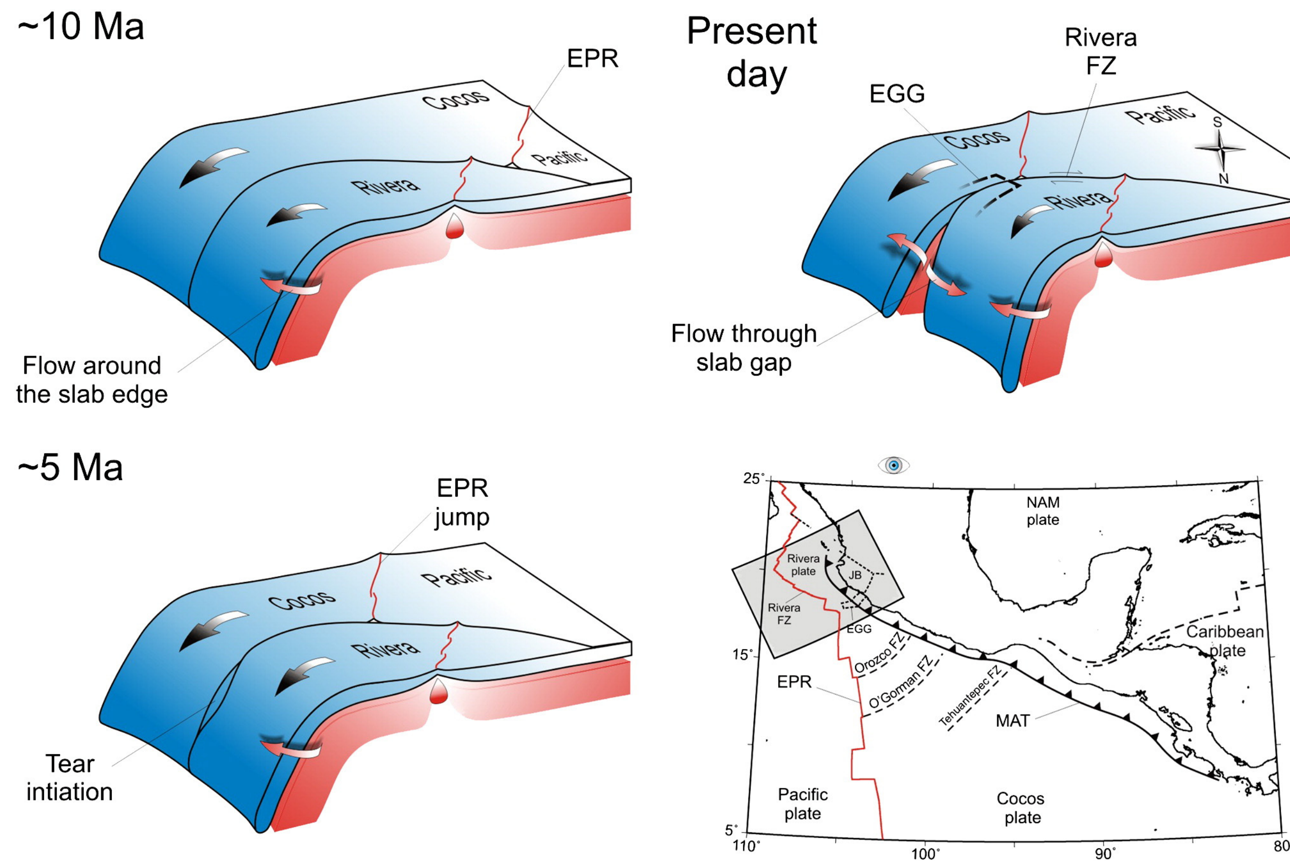

Fig. 2. Formation and development of the Rivera–Cocos slab tear and gap. The inset located on the lower left map depicts the position of the three dimensional drawings, and the blue eye marks the viewpoint of the observer.

The subducted Cocos plate beneath Mexico is characterized by a great variability and an unusual geometry along strike, inconsistent with the gradual variation in subduction parameters like plate age and convergence rate along MAT. In just a few hundreds of kilometers the slab dip varies from ~50° at the limit with Rivera plate to 0° between 100°30′ W and 97°00′ W. This flat slab subduction is one of the most intriguing features of the MASZ. Here the MASE imaged in great detail for the first time the subducted Cocos plate beneath Central Mexico (Clayton et al., 2007). The receiver function analysis of Pérez-Campos et al. (2008) combined with P and S wave tomography (Husker and Davis, 2009) imaged a flat slab segment that extends some 300 km inland from the MAT, and then sinks into the asthenosphere at a steep angle of over 65° and is finally truncated at ~500 km. Compared with the Chilean and Peruvian flat slabs, the Mexican flat slab shows significant differences that actually point to a different origin. While in Chile and Peru flat subduction induced significant shortening in the upper plate (Gutscher et al., 2000), in central Mexico this is not observed, although the Mexican flat slab has been going on longer than in the Andean cases. Data from the MASE show a 3–5 km thick layer characterized by ultra-low seismic velocity and high pore pressure (Kim et al., 2010; Song et al., 2009), which can explain the decoupling between the subducting and overriding plates. This observation confirms the numeric prediction of Manea and Gurnis (2007) that the evolution from steep slab to flat slab subduction in central Mexico should have trapped a channel of low viscosity material. The interpretation about the nature of the ultra-low velocity layer is not clear, however we propose that it actually represents a remnant of mantle wedge that experienced significant serpentinization since the flat slab established in middle Miocene (Ferrari et al., 2012). This is consistent with the low velocity nature of this layer, and with the lack of overriding plate deformation that is normally associated with coupled flat slab subduction systems (e.g. in the southern Andes). The flat slab segment of the subducting Cocos plate extends along strike a few hundreds of kilometers and is flanked by normal subduction angles of ~45°. Along MAT the flat slab region is apparently controlled by a series of fracture zones as Orozco, O'Gorman and Tehuantepec (M. Manea and V.C. Manea, 2011). In Chile and Peru, the location of flat slab areas correlates well with oceanic impactors, as ridges, or overthickened continental lithosphere, and cratons (Manea et al., 2012). However, the origin of the flat slab in Mexico still remains unclear, since there is no impactor on the oceanic plate (Skinner and Clayton, 2011). A thick lithospheric root is also absent in central Mexico as in this region the flat slab lays only a few km below the Moho. However the crust on the overriding plate consists of Precambrian and Paleozoic rocks and is up to 10 km thicker than in the region to the west and the east underlain by a ~45° slab. This thicker crust might have played a role similar to that of overthickened lithosphere in the central Andes, although this explanation needs to be proved quantitatively with detailed future numerical modeling.

Farther south the Cocos slab shows relatively uniform slab geometry beneath the Caribbean plate, with slab dip of ~50–60° beneath Guatemala, El Salvador, Nicaragua and Costa Rica (Arroyo et al., 2009; Husen et al., 2003; Protti et al., 1994; Syracuse and Abers, 2006; Syracuse et al., 2008). However, the slab dip and depth of the Wadati–Benioff zone decreases smoothly towards the southern end of the MAT from Nicaragua to Costa Rica, and further southeast there is strong evidence for a pronounced segmentation, or sharp contortion, in the Cocos slab at intermediate depth (Protti et al., 1994). The actively seismic slab terminates abruptly, and the absence of a Wadati–Benioff zone from southeastern Costa Rica through northwestern Panama corresponds to the position of a slab window created by the subduction of Cocos–Nazca spreading ridge segments since 8 Ma (Johnston and Thorkelson, 1997).

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5. Slab dynamics along MAT

As shown above, in the Mexican and Central American subduction zones there are remarkable along-strike changes in the depth and morphology of the subducting Rivera and Cocos plates, the position of the volcanic front, and the geochemistry of volcanism, yet the convergence rate and the age of the incoming oceanic lithosphere vary only slightly along MAT. To better understand the dynamic connection between the subducting Rivera and Cocos plates and the overriding North America and Caribbean plates together with the spatial and temporal variation in volcanism, in this chapter we will focus on the evolution of key aspects that have been changing along MAT since the Miocene. We start with a brief overview of the plate history and then we focus on individual regions along the MAT in order to better understand the tectonic history of the subduction system.

5.1. Plates motion around MAT since the Miocene

After the obliquely subducting Farallon plate split apart at approximately 23 Ma (Lonsdale, 2005), the Cocos plate started to subduct more orthogonally beneath NAM and Caribbean plates. At the same time internal deformation of the Chortis block basically ceased and the block became part of the Caribbean plate (Pindell and Kennan, 2009). However it continued moving eastward relative to the NAM plate along a left lateral transform boundary distributed among the Polochic, Motagua and Jocotán-–Chamelecón fault systems. Plate circuit reconstructions have shown that the Caribbean plate has been essentially stationary in the Atlantic–Indian hotspot reference frame since the Eocene (Müller et al., 1999; Pindell and Dewey, 1982), probably because it was locked by the combined effect of two opposing subduction zones on its western and eastern margins and it was trapped between the slowing converging North and South America. On the other hand the absolute motion of the NAM was basically westward, increasing to 3–4 cm/yr between 12 and 17 Ma and then decreasing to ~1–2 cm/yr after this time (Sdrolias and Muller, 2006). Also, the subducting Cocos plate shows significant changes in convergence rates along the MAT in the last 20 Ma. Based on Early to Middle Miocene Cocos–Pacific spreading rates at the EPR, Sdrolias and Muller (2006) detect an important increase in the Cocos–Caribbean plate convergence rate from ~5 cm/yr to over 15 cm/yr over a time span of 5–7 Myr. A similar convergence rate boost is observed along the northern MAT off shore Mexico between 12 and 17 Ma (Sdrolias and Muller, 2006). At present the trench-normal component of convergence of the Rivera and Cocos plates at the MAT progressively increases toward the south, from ~2 cm/yr in front of the Jalisco block to ~10 cm/yr in Costa Rica. Since the MAT corresponds to two different overriding plates it experiences a divergent dynamics. Whereas off shore Mexico the trench rolls back at 0.5–1 cm/yr, in Central America the trench advances at higher rate of 2.2 cm/yr (Schellart et al., 2007, 2008). This difference in trench dynamics along MAT has significant implications in slab dynamics that will be discussed later in the chapter "Middle America Trench Dynamics and Cocos Slab Geometry".

5.2. Rivera microplate subduction in western Mexico

Since the formation of the Rivera microplate by separation from the Cocos plate at ~10 Ma (DeMets and Traylen, 2000), the subduction zone of western Mexico was marked by slab rollback, trenchward motion of the volcanic front and extensional deformation of the overriding

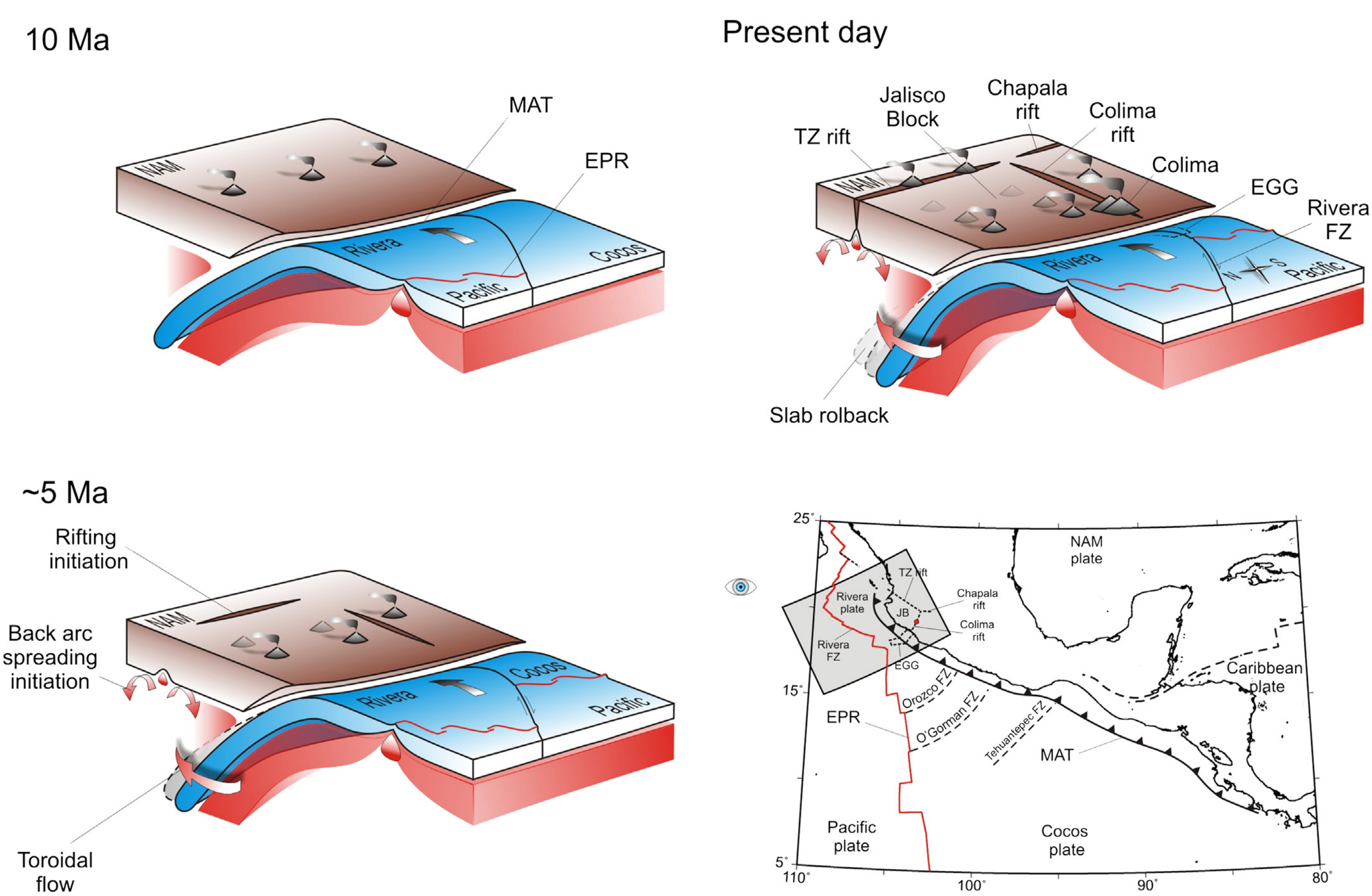

Fig. 3. Development of the Tepic–Zacoalco (TZ), Colima, and Chapala rifts. The TZ rift is formed by the Rivera slab rollback, enhanced by the toroidal flow around the slab edges. The Colima rift is probably related with the oblique convergence between Rivera and NAM plates at ~5 Ma.

plate as expressed by the Tepic–Zacoalco and Colima rifts (Ferrari et al., 2001, 2012). The geodynamic pattern in this region is further complicated by the formation of a slab gap between the Cocos and Rivera subducting plates which probably resulted in the emplacement of one of the most active and productive volcanic structure in Mexico, the Colima volcanic complex. The small and young Rivera plate represents the northwestern limit of the Middle America subduction system, so that the western edge of its slab is exposed to the hot asthenosphere ascending to feed the EPR in the mouth of the Gulf of California. As shown by Schellart et al. (2007), a small slab fragment favors faster rollback because of the onset of a toroidal flow around the slab edge that can remove the asthenosphere from under the narrow slab. Additionally, the trench starts to rollback seaward, creating favorable conditions for extensional deformation within the overriding plate. In western Mexico, two extensional corridors, the Tepic–Zacoalco and the Colima rifts, are likely formed by toroidal flows around the Rivera slab edges. The Colima rift could be generated by northwest directed toroidal mantle flow through the gap between the Rivera and Cocos slabs due to the different rollback rates between the two subduction segments (León-Soto et al., 2009) (Fig. 3). The E–W Chapala and Citlala rifts may be also related to this process, this time by northeastward toroidal flow through the Rivera–Cocos slab gap that induces a rollback of the westernmost part of the Cocos slab.

The Jalisco Block, which overrides the subducting Rivera plate, hosts a remarkable magmatic diversity in time, space and composition that derives mainly from a heterogeneous mantle source affected by the subduction agents (Ferrari et al., 2001; Gómez-Tuena et al., 2007, 2011; Petrone et al., 2003). Due to slab rollback, the volcanic front, composed primarily by subduction-related monogenetic centers, has migrated ~80 km toward the MAT in the past 10 m.y (Ferrari et al., 2000a, 2001). The Plio-Quaternary volcanic front consists of a ~60 km wide belt that runs parallel to the MAT south of the Tepic–Zacoalco rift. Here typical subduction related lavas are mixed with K_2O-rich lamproitic rocks (Lange and Carmichael, 1991). The former are associated to shallow (low P–T) melting of the peridotitic mantle wedge by fluids fluxed from the subducting slab, whereas the potassic rocks would be the results of deeper and hotter slab-derived melt due to phengite/monazite/allanite disintegration (Gómez-Tuena et al., 2011).

To the north, in the Tepic–Zacoalco rift, Plio-Quaternary volcanism consists dominantly of calc-alkaline rocks and minor amount of enriched, Na-alkaline basalts, mostly erupted by cinder cones (Ferrari et al., 2000b; Petrone et al., 2003). The Quaternary stratovolcanoes and most monogenetic cones are aligned along the main extensional fault systems. Enriched melts with OIB-like composition were suggested to have been produced by the toroidal asthenospheric flow into the mantle wedge beneath the Jalisco Block (Ferrari et al., 2001, 2012) and emplaced with only slightly to negligible interaction with the crust due to the extensional tectonic regime in the overriding plate (Petrone et al., 2012).

The oblique convergence between Rivera and NAM plates at ~5 Ma (DeMets and Traylen, 2000) induced a component of dextral shear along the MAT (Kostoglodov and Bandy, 1995) and therefore tensional stresses in the Colima rift (Fig. 3). This period coincides with the onset of alkaline volcanism in the northern part of the Colima rift (Allan, 1986), which lies approximately above the seismically imaged gap between the Rivera and Cocos plates. Several authors proposed that a tear between Cocos and Rivera boundary might be responsible for the location of the Colima volcanic complex (Bandy et al., 1995; Nixon, 1982; Yang et al., 2009). However, there are several characteristics that, in our view, make such hypothesis inaccurate. In fact the gap within the high-velocity seismic anomaly becomes apparent only at ~150 km depth (Yang et al., 2009) so that it does not coincide with the location of Colima volcano, which lies ~100 km above the boundary between Rivera and Cocos slabs. In this region the mantle flow is likely dominated by the mantle wedge poloidal flow rather than the toroidal flow. Here we propose that the position and high magmatic productivity observed at the Colima volcanic complex is rather caused by the subduction of the Rivera–Cocos plate discontinuity. The intersection of the Rivera Fracture Zone with the MAT coincides with a deep trough bounded by high scarps (Mammerickx and Klitgord, 1982), the El Gordo Graben (Bandy et al., 2000). Serpentinization of the oceanic mantle entering subduction zones around the Pacific has been proposed to occur along deep faults where oceanic plates enter into subduction (Dzierma et al., 2012a,b; Omori et al., 2002). Located in an active subduction system, these serpentinized structures act like a temporary water storage carrier, as they store fluids through seawater infiltration and peridotite serpentinization. Then, as the subducting slabs dive into the hotter asthenosphere, the stored water is released back into the overlying mantle wedge producing abundant volcanism (Manea and Manea, 2008). Subduction of serpentinized fracture zones enhances melting production in the mantle wedge and, at the same time, can influence the position of the melting front (Fig. 4).

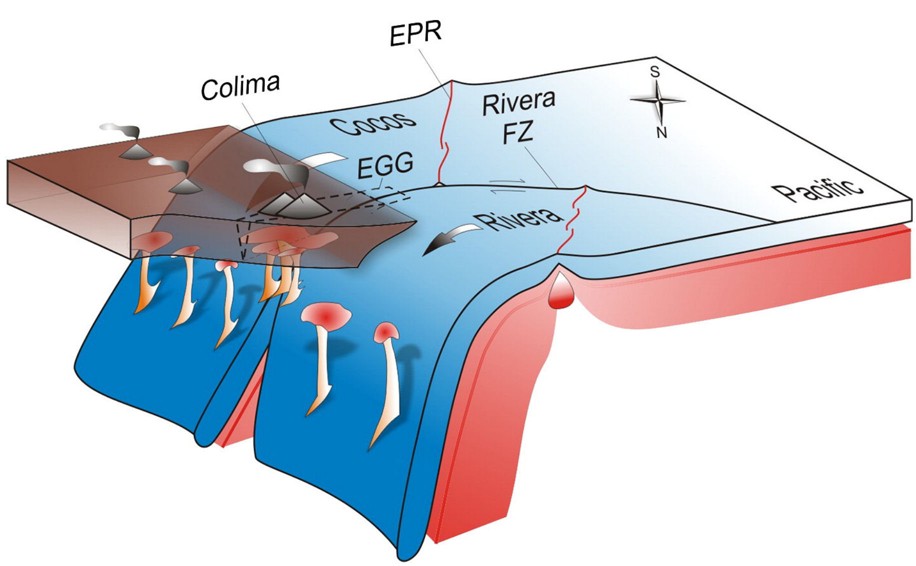

Fig. 4. Proposed model for the formation of the Colima volcanic complex by subduction the extensional and hydrated oceanic crust of the El Gordo Graben (EGG). The subduction of the EGG enhances melting production in the mantle wedge. Red "mushrooms" in the mantle wedge portray the melting anomalies feeding the volcanism.

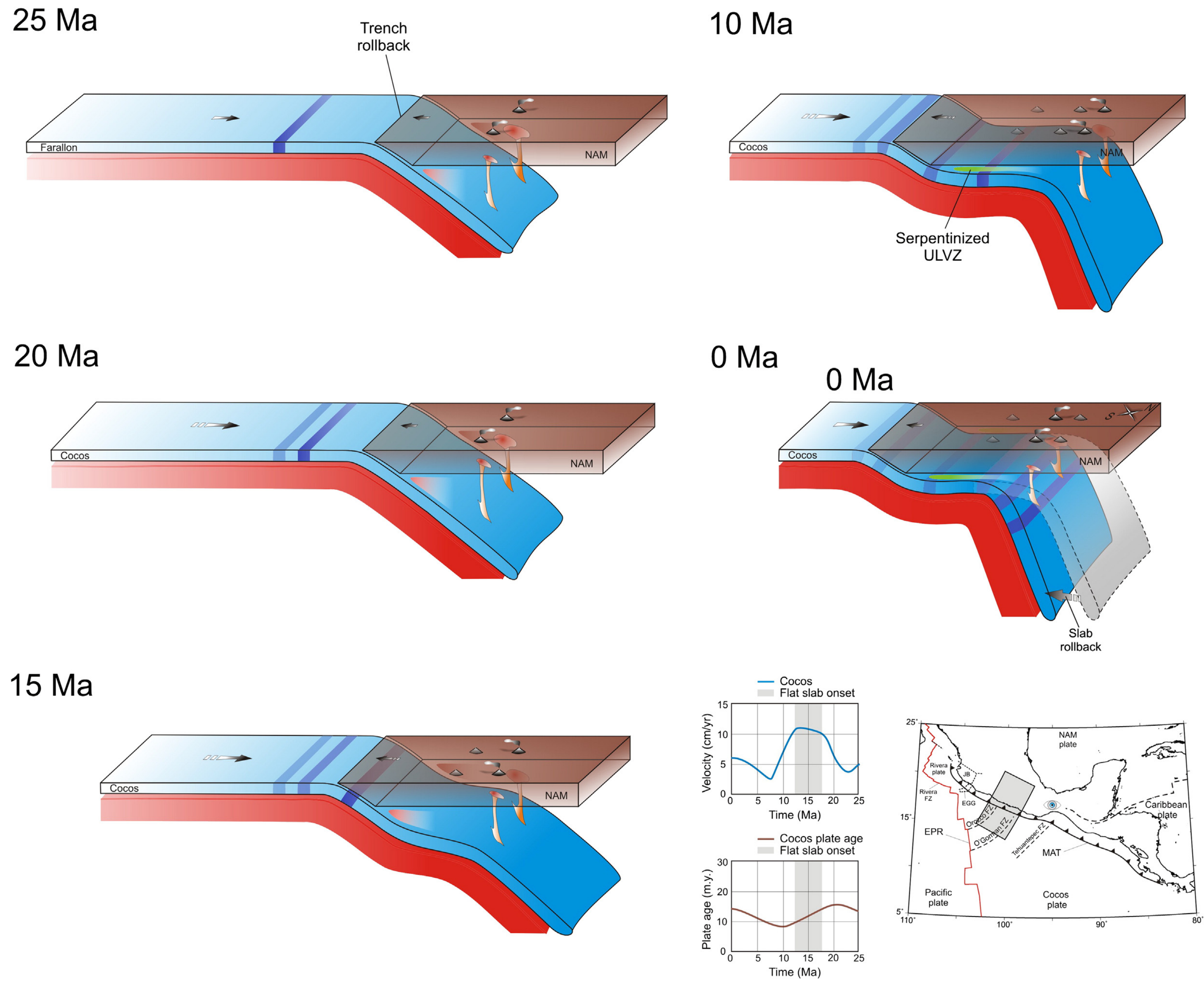

Fig. 5. Evolutionary model for the subducting system beneath Central Mexico (approximately between 100°W and 97°W). The slab flattening process is proposed to have initiated by the combination of rapid increase in Pacific-Cocos spreading rates at 17 Ma, a very young subducting plate (8–9 Ma) and the MAT rollback. The blue strips represent markers on the Cocos plate. Inset in the bottom-right corner show Cocos convergence velocity and age of the plate at the trench based on Sdrolias and Muller (2006).

5.3. Slab flattening in central Mexico

The origin and dynamics of flat slab in central Mexico is clearly the most controversial and enigmatic phenomena along the MAT. Isotopic ages of magmatic rocks for the TMVB show the initiation of a clear inland migration of the volcanic front at ~16 Ma (Ferrari et al., 2012). These notable changes in the location of volcanism in central Mexico are attributed to changes in the Cocos slab geometry. The rapid migration of volcanism away from the trench in mid Miocene marks the initiation of flat slab subduction in this part of Mexico, which reaches its maximum extension at ~10 Ma when it started to migrate back towards the MAT (Fig. 5). In the last decade, several attempts were made to provide a plausible explanation for the origin of flat slab in central Mexico. However, the lack of a buoyant oceanic impactor (i.e. ridge or plateau) (Skinner and Clayton, 2011), the little variation in plate age along the MAT offshore central Mexico for the last 30 Myr (Sdrolias and Muller, 2006), and the absence of a over-thickened continental lithosphere (150–200 km) in the proximity of the mantle wedge, recently proposed to explain shallow subduction in South America (Manea et al., 2012), made even more puzzling the flat slab subduction. Here we propose a new hypothesis, where the rapid increase in Pacific-Cocos spreading rates from ~4 cm/yr to ~12 cm/yr around 15 m.y. ago (Sdrolias and Muller, 2006), coupled with a young subducting plate and trench rollback, has the real potential to induce flat slab subduction. Recently, Manea et al. (2012) showed that trench roll back is a minimum requirement for flat slab formation, and that trench roll forward prevent shallow dip angles, but rather induce steep subduction. This scenario may be investigated with further 3D numeric modeling tailored specifically for the time-space variation of subduction parameters along MAT offshore central Mexico. In Fig. 5 we present schematically the time sequence of such flat slab subduction mechanism in central Mexico.

The slab flattening in central Mexico at 16 Ma must have changed the mantle dynamics also in the nearby southeastern Mexico region. The time-space effect of such large-scale tectonic process can be better understood looking at the spatial variation through time of volcanic arcs. Here, we base our interpretation on the distribution of dated rocks from Ferrari et al. (1999 and 2012) for Central México and from Damon and Montesinos (1978) for southeastern Mexico. After the

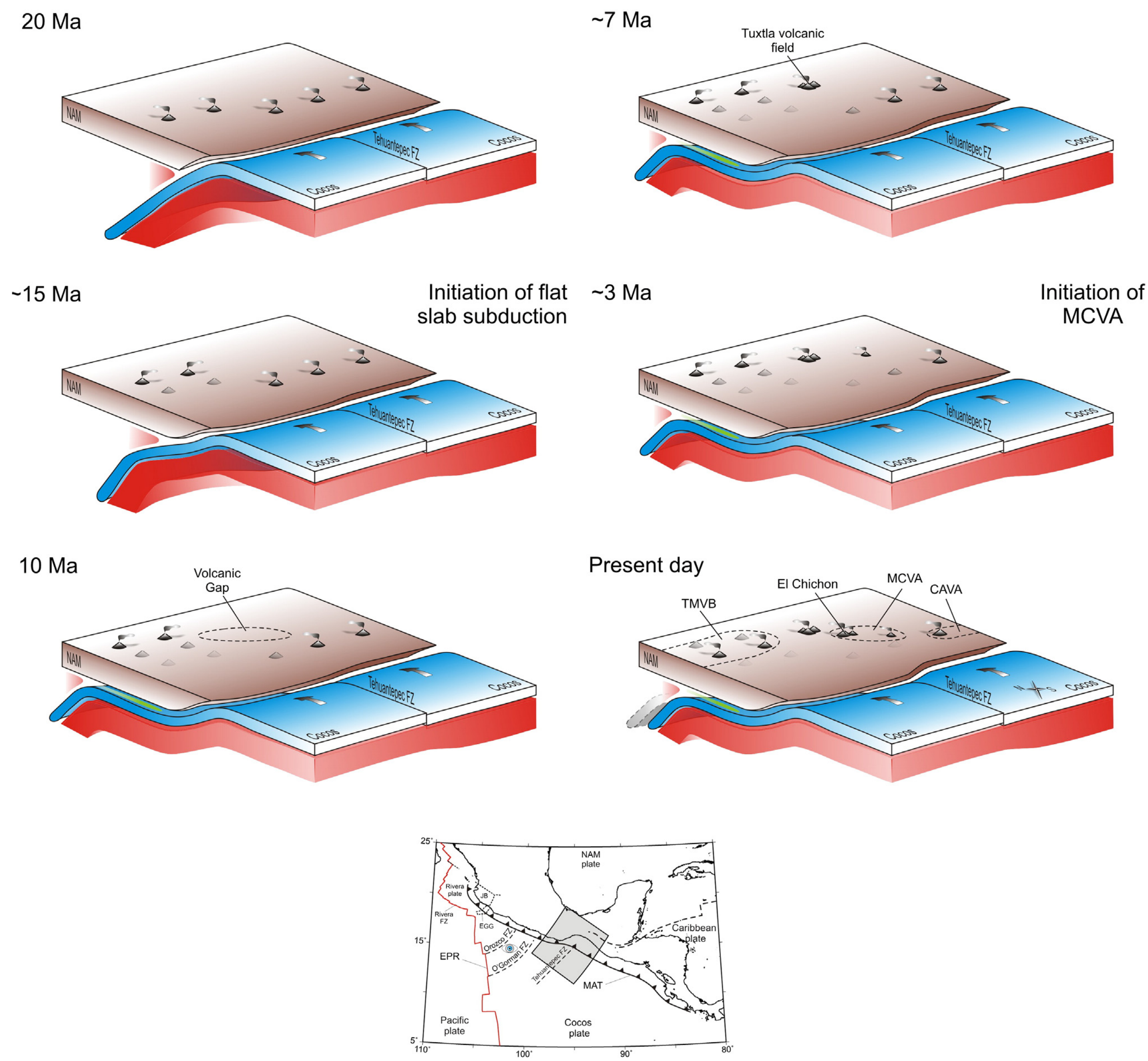

Fig. 6. Northwest directed view showing the effect of slab flattening and subsequent rollback in controlling the migration of volcanism and the lateral development of volcanic gaps. Volcanic gaps would be generated by the mantle squeeze during slab flattening and the creation of cold wedges (probably serpentinized) at the sides of the flat slab (see Fig. 7).

onset of flat subduction, the CAVA started retreating from the Isthmus of Tehuantepec towards the southeast, leaving behind a volcanic gap several hundreds of kilometers wide. At 7–10 Ma the volcanic activity in southern Mexico ceased completely, but it resumed near the Gulf of Mexico coast in the vicinity of the Isthmus of Tehuantepec, when the Tuxtla Volcanic Field was formed. The last episode of this readjustment occurred between 3 and 0 Ma with the formation of the MCVA and the onset of El Chichón. On the other side of the flat slab area, in the western TMVB, a gap in volcanism is also observed between ~18 and 11 Ma, which broadly corresponds to the onset and development of the flat slab (Ferrari et al., 2012, Fig. 9a). The gap is later filled once the slab starts to rollback since the Late Miocene. We interpret this progressive volcanic arc readjustment as the consequence of mantle flow reorientation due to slab flattening, inducing toroidal flows at the edges of the flat slab area. Seismic anisotropy (Russo and Silver, 1994) and numerical modeling (Kneller and van Keken, 2007, 2008) support this scenario and show that trench-parallel flow can develop during the flattening of slabs. As the slab progressively flattens the mantle in the wedge need to be pushed laterally out of the area of slab flattening, favoring the trench-parallel flow rather than the trench-perpendicular flow. On the other hand the progressively flatter slab induce a decrease in temperature in a wide belt around the flat area. The combination of lateral squeeze of the mantle contained in the wedge and the cooling effect around the flat slab area provides a plausible explanation for the volcanic gap between TMVB and CAVA and in the western TMVB. The time sequence of this mechanism is shown in Fig. 6.

5.4. Tehuantepec fracture zone subduction in southern Mexico

The Tehuantepec fracture zone (TFZ) is one of the most prominent bathymetric features on the Cocos Plate, and separates the Cocos Plate in two parts with distinct tectonic regimes and age (Klitgord and Mammerickx, 1982; Manea et al., 2003; Wilson, 1996). This fracture zone interrupts the MAT outer rise in the vicinity of the ocean-ward concave bend in the trench axis in the Gulf of Tehuantepec (Fig. 1), where the age of the subducting plate sharply increases from 16 Ma to 26 Ma (Manea et al., 2003). Several other characteristics make the TFZ a distinct bathymetric anomaly among other fracture zones observed on the Cocos plate. Manea et al. (2005) proposed that the TFZ was the result of compressive deformation that created a series of faults that cuts across the whole oceanic crust, allowing the seawater to interact with the upper mantle. The PT conditions beneath the TFZ favored the transformation of the mantle peridotite into serpentinite, a hypothesis confirmed by the strong magnetic anomalies observed along TFZ (Manea et al., 2005). The TFZ also appear to control the geochemistry of the El Chichón volcano, which lies along its onshore prolongation. Located at the northwestern end of the MCVA, El Chichón shows a K-rich magma signature that departs from the otherwise typical calc-alkaline composition of this arc. Normally, wedge serpentinite are relatively low in alkalis, but the fluids released during dehydration may be moderately rich in alkalis because they preferentially enter the fluid phase (Scambelluri et al., 2001). The thermomechanical model for southern Mexico of Manea and Manea (2008) shows that slab dehydration along the subducting TFZ occur at depths comparable with the slab depth beneath El Chichón, suggesting that fluids released from serpentinized mantle may be a potential source for the K-rich rocks of El Chichón (Fig. 7). The substantial influx of fluids from the slab into the overlying mantle has also the capability to produce adakitic magmatism (Macpherson et al., 2006). However, whether El Chichón holds a real adakitic signature or not, need further studies.

5.5. Slab window in Central America

From southern Mexico through southern Costa Rica the Cocos slab is continuously subducting beneath the Caribbean plate with dip decreasing from ~60° below Guatemala to ~30° beneath central Costa Rica. However, farther southeast, approaching the Cocos–Nazca–Caribbean triple junction, the Cocos slab is not seismically imaged below ~70–100 km (Dzierma et al., 2011; Protti et al., 1994). The absence of a Wadati–Benioff zone from southeastern Costa Rica through northern Panama suggests the existence of a slab window in this region (Johnston and Thorkelson, 1997). Other evidences in favor of a slab window come from geochemical variations of Quaternary volcanoes along the CAVA. The increase in OIB-like chemical signature toward the triple junction suggests that the mantle in this area is dominated by an enriched source (Herrstrom et al., 1995), probably coming from the Galapagos hotspot, which can flow within a slab window with little or no mixing with the subduction-metasomatized mantle wedge (Abratis and Wörner, 2001). Moreover, above the edged of the proposed slab window in southern Costa Rica and northern Panama, typical arc volcanism is replaced by adakitic rocks (DeBoer et al., 1995). As in the case of the Rivera subduction zone, the slab window between the Cocos and Nazca plates creates the right conditions for toroidal flow and influx of enriched hot sub-slab mantle into the adjacent regions. The exposure of the slab edges bounding the slab window to this hot mantle creates the conditions for slab melting (e.g. Yogodzinski et al., 2001). From a purely kinematic point of view, the evolution of plate interaction in this area satisfies the necessary conditions for the existence of a slab window. In fact the subduction of the Panama fracture zone coupled with the strong divergence and different plate velocities between the Cocos and Nazca plates (Fig. 1), make the formation of a slab window inescapable. Johnston and Thorkelson (1997) show that the slab window began between 6 and 10 Ma and is currently expanding and migrating northeastward below the CAVA. In Fig. 8 we show the time sequence for the Cocos and Nazca plates tectonic evolution and the development of slab window beneath CAVA.

5.6. Slab detachment in the Middle America subduction zone

One consistent feature of the Rivera and Cocos plates subducted beneath the NAM and Caribbean plates is the abrupt termination of the slab well above the transition zone. The regional S wave tomography of Van der Lee and Nolet (1997) shows two separate sub-parallel slab anomalies beneath northern and central Mexico. More detailed P and S wave tomography along the MASE show the slab truncated at ~500 km of depth and a detached high velocity anomaly starting at ~650 km of (Husker and Davis, 2009). Similarly, P-wave tomography profiles at the longitude of the Tehuantepec Isthmus, eastern Guatemala, and central Nicaragua (Rogers et al., 2002), show a gap in the Cocos slab between ~300 and 500 km of depth. Rogers et al. (2002) report geologic evidences of a Late Miocene epeiorogenic uplift of the region underlain by the slab gap in Honduras and conclude that a detachment of the slab must have occurred here between 9 and 3.8 Ma. Ferrari (2004) uses the geologic record of the TMVB to support the case for a lateral propagation of detachment from the Gulf of California to southeastern Mexico in Late Miocene. In his model the detachment initiated in the Gulf region as the Magdalena microplate (Farallon remnant) stop subducting at ~12.5 Ma off Baja California and a trench sub-parallel tear propagated eastward because of the increased slab pull of the still attached lower slab. The slab detachment is considered to have caused a distinctive pulse of mafic volcanism that migrate from ~11 Ma in the western TMVB to ~6.5–5 Ma in the eastern TMVB and Los Tuxtlas volcanic field (Ferrari, 2004; Ferrari et al., 2000a, 2005). Based on this record the detachment at the longitude of Mexico City should have occurred at ~7 Ma, a timing consistent with the length of the Cocos slab imaged by the MASE experiment (Ferrari et al., 2012, Fig. 17). It is very likely that the tear in the slab keep propagating to the east-southeast, reaching Central America at the end of Miocene. If this is the case the detachment would have propagated over a length of approximately 2000 km in ~7 Ma, with an average rate of ~300 km/my. However, a faster rate of

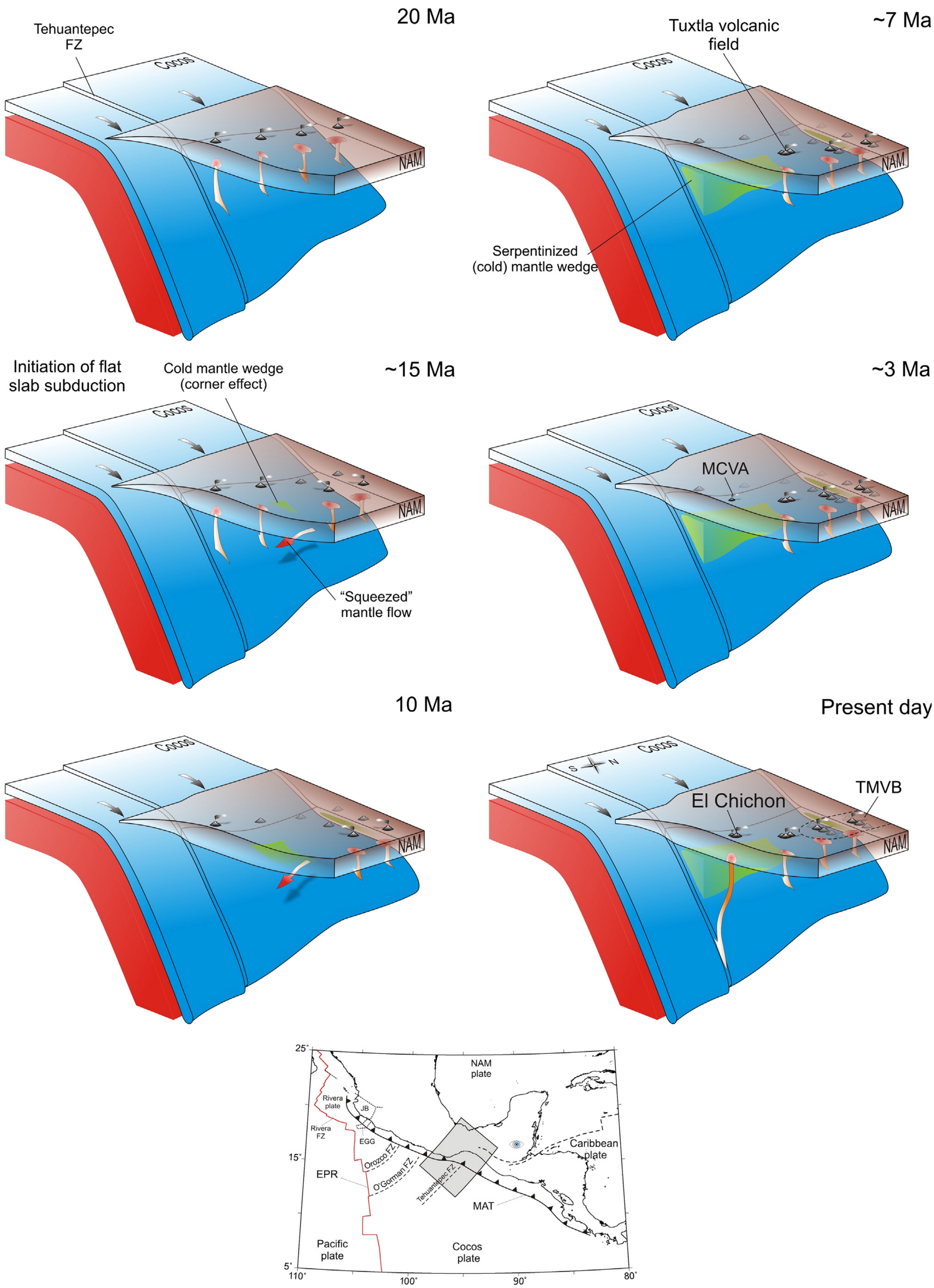

Fig. 7. Southwest directed view of the subduction of the Tehuantepec fracture zone and formation of El Chichón volcano by deep dehydration due to the presence of a cold and serpentinized mantle wedge at shallower depths.

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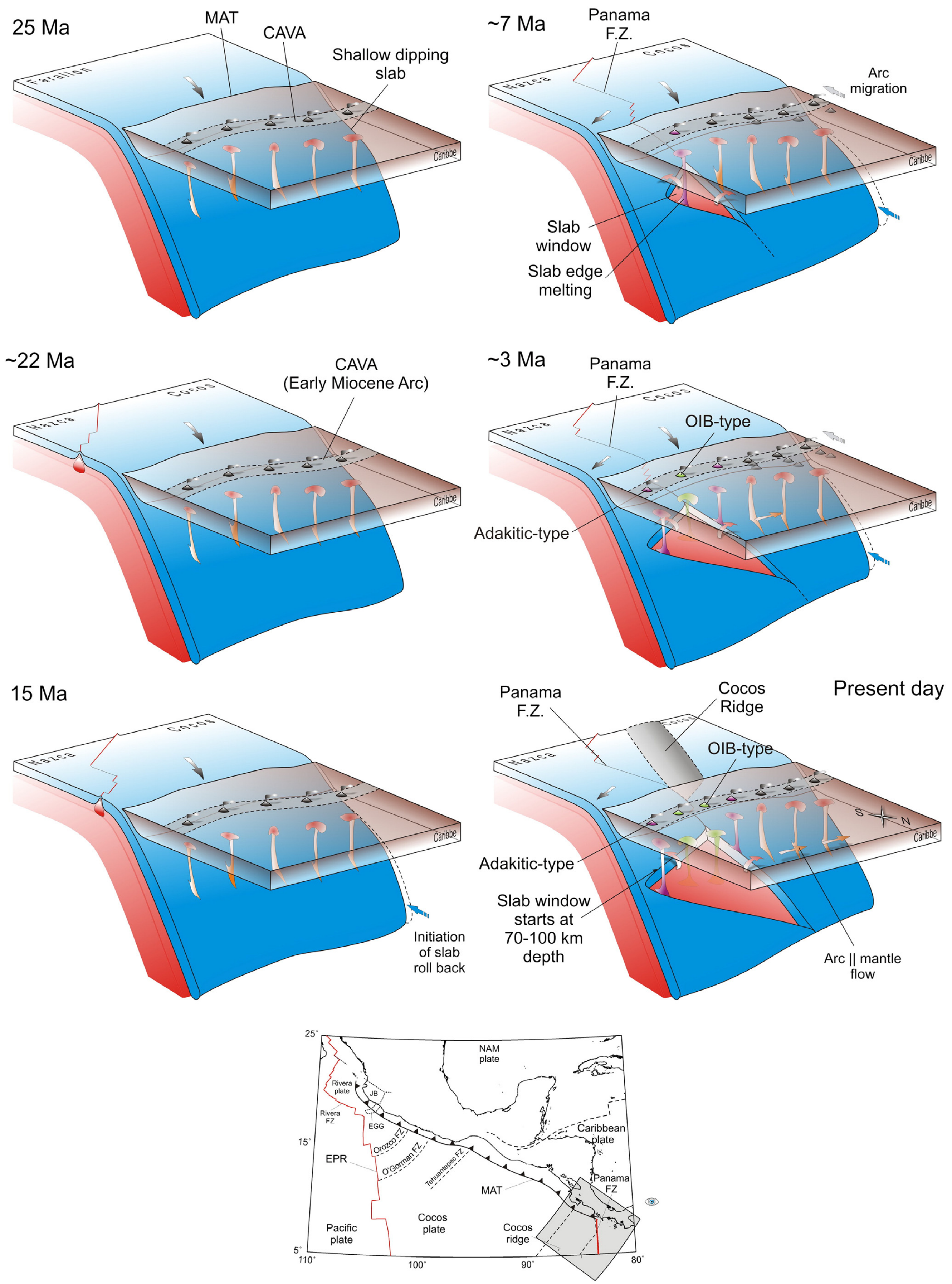

Fig. 8. Southwest directed view of the tectonic evolution of the Cocos and Nazca subduction and the development of the Central America slab window beneath the CAVA.

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detachment is observed in western Mexico (Ferrari et al., 2012) in agreement with predictions of 3D numerical models in the case of young plates (Van Hunen and Allen, 2011).

A Late Miocene episode of slab detachment along the MASZ has important implications for the geodynamics of the region. The progressive break off of the lower part of the slab has the direct consequence of allowing sub-slab asthenosphere to enter the mantle wedge. This low viscosity and hotter material would favor the decoupling between slab and the upper plate and the development of trench perpendicular slab tears and slab window by reducing the slab pull. Interestingly, the convergence velocity of the Cocos plate shows a sharp decrease in Late Miocene, during the progress of the detachment. Moreover, the trenchward motion of the TMVB since 10 Ma and the corresponding slab rollback of the previously flat slab may have been favored by the detachment, as the low viscosity mantle start to infiltrate between the upper and lower plates. In the case of Central America, although less pronounced than the TMVB, the CAVA has also migrated toward the trench since ~11 Ma (Alvarado et al., 2007). Finally, the initiation of detachment in the Gulf of California at ~11 Ma may have also favored the individualization of the Rivera plate which shows a motion independent from the Cocos plate at 10 Ma (DeMets and Traylen, 2000).

6. Evaluating slab dynamics in the context of present-day geophysical observations

Despite the relative abundance of geophysical observations along the Middle America subduction zone, there are still large gaps in our knowledge about how subduction zones and plate tectonics influence one another. The geophysical studies published in the last few years can be used to propose evolutionary models for the whole MAT subduction system. In this chapter we evaluate the relationship between present-day observations, geodynamic setting and slab dynamics along MAT.

6.1. Intraslab seismicity and flat slab subduction relationship

Almost the entire length of the Middle American margin has ruptured repetitively in the past few centuries, as the Cocos and Rivera plates subduct beneath North American and Caribbean plates along the MAT (Fig. 1). It is well known that the complexity inherent in the geologic structure of both Cocos and Rivera oceanic plates, such as seamounts and fracture zones, affects the occurrence of large shallow-depth earthquakes (Kostoglodov and Ponce, 1994). Although there are strong correlations between observations and models for shallow inter-plate seismicity, the origin of intermediate-depth earthquakes within the subducting oceanic slabs is not entirely understood. Over the last decades, several mechanisms for intra-slab seismicity generation have been proposed. Among these, slab dehydration, bending stresses, slab pull, and thermal stresses are the most popular factors that might control the occurrences of intra-slab earthquakes (Hacker et al., 2003; Kanamori, 1971; Manea and Manea, 2006; McGuire and Wiens, 1995; Peacock, 2001; Turcotte and Schubert, 2002).

In central Mexico, the flat slab segment of the subducting Cocos plate is characterized by sparse intra-slab seismicity with downdip T axes (Manea and Manea, 2006). This contrast with other flat slab subduction zones where the intra-slab seismicity is abundant, as is the case of Chilean and Peruvian flat slabs (e.g. Gutscher, 2002; Pardo et al., 2002). The cause for this peculiar seismic response and the state of stress in the flat slab area in central Mexico is still unknown. Below, we discuss the possible links between intra-slab seismicity and models, trying to offer a plausible explanation for this rather unusual seismic behavior in this region.

The flat slab segment in Mexico is where most of the oceanic crust undergoes dehydration (V.C. Manea and M. Manea, 2011), but there is little intra-slab seismic activity in that region. This seems to contradict the dehydration embrittlement hypothesis, which states that earthquakes are triggered in subducting slabs where strong dehydration is expected (Hacker et al., 2003). On the other hand, Isacks and Barazangi (1977) proposed that intra-slab seismicity might be the result of bending/unbending of the slab. However, this model does not explain either the seismicity of central Mexico because intra-slab events are not restricted to those parts of the Cocos slab that undergo changes in curvature. A third model to explain tensional intra-slab seismicity was put forward by Isacks and Molnar (1969), who suggest that shallowly penetrating slabs are in down dip tension as a result of negative buoyancy with respect to the asthenosphere. In this model the stresses are transferred from the deeper parts of the slab to the upper part through the elastic core within the negatively buoyant slab. The elastic thickness of oceanic plates depends on plate age and curvature (Burov and Diament, 1995), and increases as a function of plate age (Watts, 2001). For example along the MAT, the elastic thickness of the Cocos plate varies from ~8 km offshore Mexico to ~12 km offshore Central America (Bry and White, 2007). In central Mexico, the MASE results revealed that the slab sharply plunges into the mantle at a steep angle of 65°–70° inland of the flat

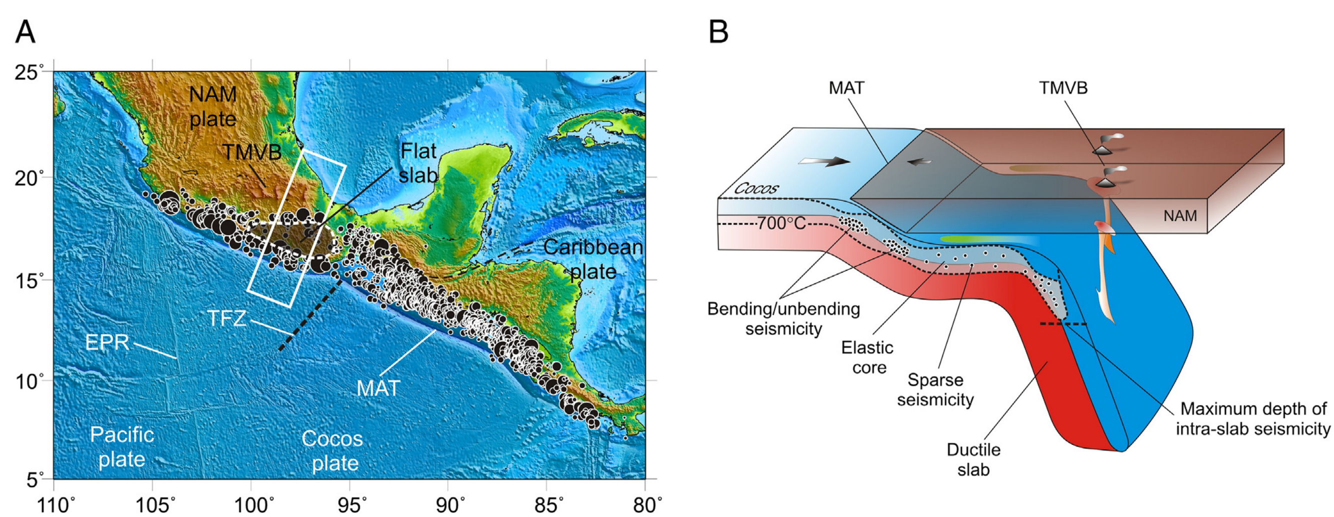

Fig. 9. A. Seismicity associated with the Middle America Subduction Zone. Note the low level of intra slab seismicity associated with the flat slab segment beneath Central Mexico. B. Schematic view of the geometry and thermal structure of the Central Mexico subduction zone based on V.C. Manea and M. Manea (2011). The scarce seismicity observed in the Mexican flat slab segment might be the combination between reduction of the elastic core after bending and the loss of rigidity (hot slab) of the Cocos slab at greater depths.

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subduction region (Fig. 1). Such a tight slab bending is likely to reduce considerably the thickness of the elastic slab core strongly diminishing the ability to transmit stresses from large depths to the flat slab segment. Moreover, the slab thermal structure (V.C. Manea and M. Manea, 2011) indicates that the maximum depth extent of the 600–700 °C isotherms, which delimits the mechanically strong part of the lithosphere (Bodine et al., 1981; Cloetingh and Burov, 1996; Watts et al., 1980), is at 70–100 km depth, which is right below the hinge region depth. The intra-slab seismicity vanishes at ~100 km depth, suggesting that below this depth the slab behave in a ductile way. Combining together these observations, a picture of a key connection between seismicity, slab geometry and thermal state emerges. We suggest that the deeper part of the subducting Cocos slab has essentially no rigidity and is thus unable to transmit any stress to the shallower flat slab segment, explaining the scarcity of intra-slab earthquakes in this area (Fig. 9). However, other stress generation mechanisms, like thermally induced contraction (Manea and Manea, 2006), may contribute to the low level and scattered seismicity observed in the flat slab area.

6.2. Moho depth and slab dynamics along MAT

Crustal thickness and structure play an important role in arc volcanism and petrology (Carr, 1984; Gómez-Tuena et al., 2007; Wallace and Carmichael, 1999), deformation of the upper plate (Ferrari et al., 2012), and subducting dynamics (Manea et al., 2012). The crustal structure and thickness of the overriding plates along MAT is seismically imaged by a number of recent experiments: Dzierma et al. (2010), MacKenzie et al. (2010) for Costa Rica and Nicaragua, Narcia-Lopez et al. (2004) and Bravo et al. (2004) for southern Mexico, Zamora-Camacho et al. (2010) and Melgar and Pérez-Campos (2011) for the Isthmus of Tehuantepec-Mexico, MASE for central Mexico (Pérez-Campos et al., 2008) and MARS for western Mexico (Yang et al., 2009). A summary of crustal thickness from these experiments is presented in Fig. 10 together with the contours of Moho depth obtained by the interpretation of Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite gravitiy data (Reguzzoni and Sampietro, 2012).

Crustal thickness estimates for Central America from the above experiments show little variation, with Moho depths commonly around ~35 km in the thickened oceanic arc crust of the Chorotega block. Receiver function analysis (Dzierma et al., 2010) in south-central Costa Rica imaged the upper plate Moho, revealing a relatively constant crustal thickness of ~35 km. A similar Moho depth of ~35 km was also observed for northern Costa Rica (Mackenzie et al., 2008, 2010) although in the oceanic accreted terrane of the Nicoya peninsula it decrease to 22–27 km and it may reach 42 km in the northern part of the Talamanca Cordillera (Linkimer et al., 2010). The thickness of the crust of the Chortis block shows similar variation. Here the accreted oceanic arc of the Siuna Terrane in Nicaragua range between 31 and 37 km (Linkimer et al., 2009) and the thinnest crust (26 km) lies directly beneath the volcanic arc (Mackenzie et al., 2010). The crust of the northern Chortis block, in Honduras, is up to 40 km thick, in agreement with the continental nature of this terrane.

Moho depth estimates in Mexico show strong crustal thickness variations compared with Central America. In southern Mexico, beneath Chiapas, the thickness of the continental crust decreases

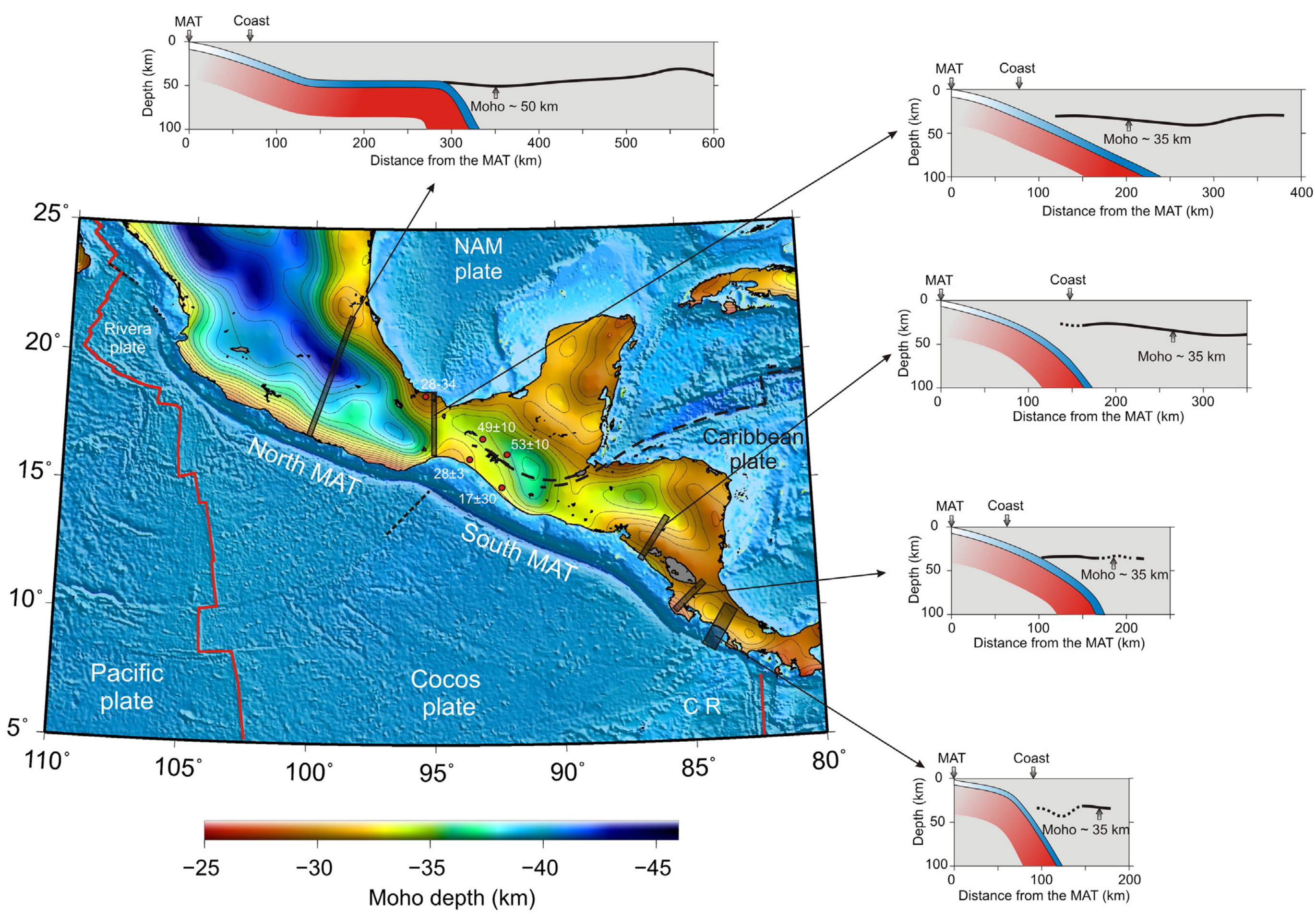

Fig. 10. Moho topography for Mexico and Central America: Moho map is based on gravity GOCE data (Reguzzoni and Sampietro, 2012). 2D profiles represent Moho and slab geometry and are based on seismic experiments (Dzierma et al., 2010; Mackenzie et al., 2010; Melgar and Pérez-Campos, 2011; Pérez-Campos et al., 2008). Red dots depict point Moho depth estimations from seismic experiments (Narcia-Lopez et al., 2004; Zamora-Camacho et al., 2010). Other notations are as in Fig. 1.

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rapidly toward the MAT, from 49–53 km inland to only 17–28 km beneath the coast (Narcia-Lopez et al., 2004). Farther north, in the Isthmus of Tehuantepec (see Fig. 10), a detailed Moho topography was revealed recently by stacking receiver functions (Melgar and Pérez-Campos, 2011). Compared with Moho depth beneath Chiapas, crustal thickness varies little here, from ~30 km, for the continental shelf of the Gulf of Mexico beneath the Los Tuxtlas volcanic field (Zamora-Camacho et al., 2010), to ~40 km for the middle part of the Isthmus (Fig. 10). The region with the thickest Moho along MAT is located beneath the eastern part of the TMVB, with maxima over 50 km. Westward, the Moho depth diminishes again to ~35–40 km depth.

The Moho depths reported by the seismic experiments are also confirmed in the global 3D high-resolution map of the Moho based on data from ESA's GOCE gravity satellite. The GOCE Exploitation for Moho Modelling and Applications project (GEMMA) has now generated the global high-resolution Moho map (Reguzzoni and Sampietro, 2012). Compared with Moho estimates along 2D seismic profiles, one major advantage of GEMMA is the possibility to visualize Moho geometry in 3D. The Moho depth estimates from GEMMA show a relatively uniform crustal thickness in southern Central America, but a thicker Moho in the continental part of the Chortis block in Honduras and a more variable Moho for Mexico (Fig. 10). The thicker crust beneath the eastern TMVB correlates well with the location of the flat slab segment in central Mexico, suggesting an intrinsic connection; in fact flat slab subduction zones with trench retreat are associated with regions of thickened overlying plates (Manea et al., 2012). Another region on thick crust is visualized in southern Mexico, in the Chiapas state (Fig. 10). Here the Cocos plate plunges into the mantle at a normal angle (see Fig. 1b), which apparently seems to contradict the above conclusion. However here the Cocos plate subduct beneath the Caribbean plate and the MAT does not retreat but rather advances. Therefore it is not able to generate a flat subduction. Also, another important feature for this region is the general shallowing of the Moho towards the MAT, from ~50 km inland to only 17–28 km beneath the coast. Narcia-Lopez et al. (2004) suggest that lower upper mantle densities beneath the coast push Moho to shallower depths and are responsible for this rapid crustal thinning. This agrees with the work of Manea and Manea (2008), who proposed the existence of a partially serpentinized mantle wedge beneath the southern Mexican coast (see Fig. 7) that is confirmed by the relatively low upper mantle a S-wave velocity estimate beneath the coast (4.1 km/s, Narcia-Lopez et al., 2004), a typical value for partially serpentinized ultramafic rocks (Kern and Tubia, 1993; Watanabe et al., 2007). A region of thickened crust is observed at the continental boundary between the North America and Caribbean plates on both sides of the Polochic–Motagua fault zone in the GEMMA model (Fig. 10), although the Moho depth imaged by this method is less than that of deduced by (Narcia-Lopez et al., 2004). However they mostly coincide with the Moho estimated by Franco et al. (2009) from receiver function analysis. These authors found a ~35 km deep Moho north of the Polochic fault and south of the Motagua fault, while the region in between is characterized by a 4-to-6-km thinner crust or by a 6–7% decrease of the *Vp*/*Vs* ratio. A moderate thickening of the North America crust in proximity to its interaction with the Caribbean plate is consistent with the long-term deformation history of this plate margin, which has been characterized by collision and transpression during the most of its evolution.

6.3. Slow slip, NVTs and slab roll back

Over the last decade, high-precision GPS measurements carried out along active convergent margins around the world revealed the

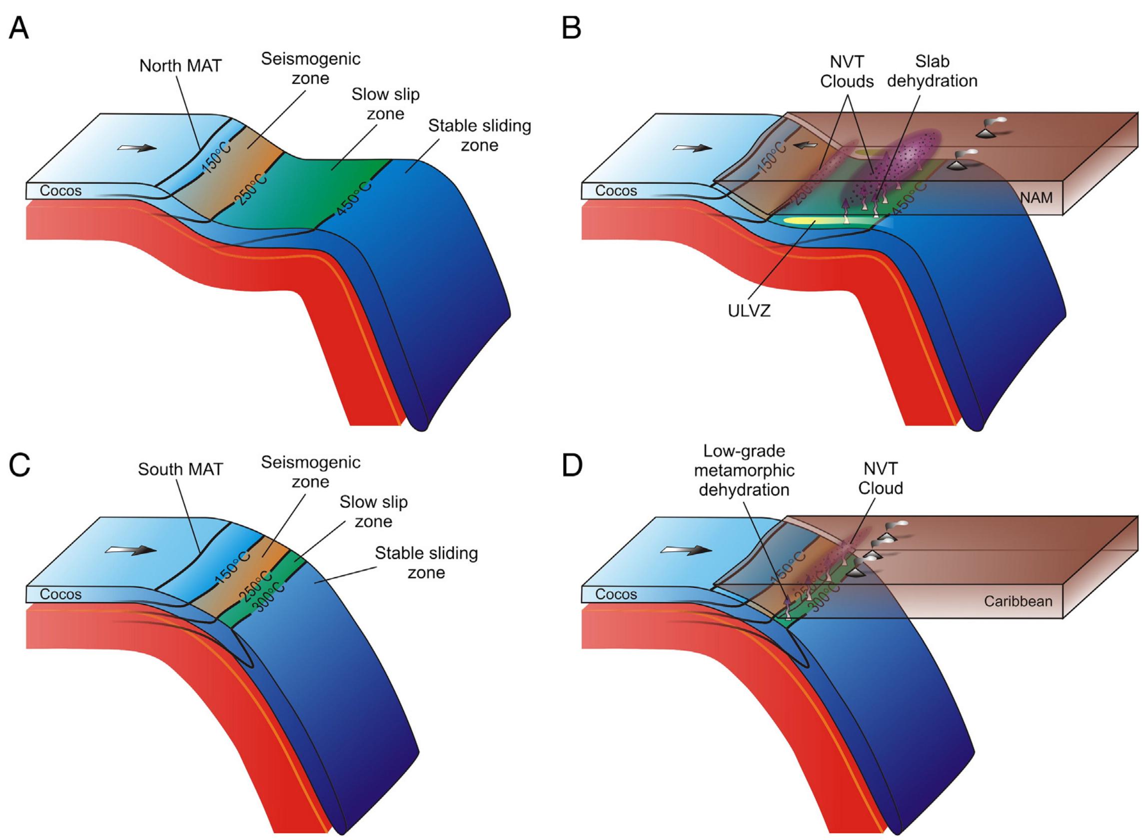

Fig. 11. Comparison between the thermal structure and geometry of the Mexican flat slab region (A) and the Central America steep slab region (C). The difference in thermal structure, amount of fluids released, slab geometry and the length of the conditionally stable slab segment control the location of slow slip events. In panels B and D we show the good correlation between the dehydration fronts and the location of recorded Non Volcanic Tremors (NVTs) in both regions, suggesting a possible relationship between the two phenomena. ULVZ = Ultra Low Velocity Zone (Song et al., 2009).

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occurrence of slow aseismic slip events (SSEs) (Dragert et al., 2001; Hirose et al., 1999; Ozawa et al., 2001). The MASZ is no exception, and several episodes of SSE have been recorded, being those above the flat slab region of central Mexico, the largest reliably detected events (Kostoglodov et al., 2003). While the average displacements of other SSEs are in the range of several cm, the 2001–2002 SSE recorded in central Mexico had an average slip of ~10 cm and produced measurable displacements over an area of ~550 × 250 km^2 with the equivalent moment magnitude of a Mw ~7.5 event. In comparison, the 2003 SSEs recorded in Costa Rica at the Nicoya peninsula had an average slip on the plate interface of only 1.5 ± 0.5 cm (Schwartz and Rokosky, 2007), almost one order of magnitude smaller than the 2001–2002 central Mexico event. The updip and downdip limits of the seismogenic (Dixon and Moore, 2007) and SSEs regions have been attributed to a certain temperature range. The seismogenic, coupled zone, where large interplate earthquakes often occur, is confined between ~150 °C and 250 °C–300 °C isotherms, and the partially coupled (conditionally stable), transient zone, is delimited by 250 °C–300 °C and 450 °C isotherms (Blanpied et al., 1995; Hyndman and Wang, 1993; Tse and Rice, 1986). However, in Costa Rica beneath the Nicoya peninsula, SSEs occur where the slab temperatures are ~100 °C lower than in Mexico and other subduction zones (Brown et al., 2009; Norabuena et al., 2004; Outerbridge et al., 2010). Inversion of the surface displacement data shows a peak slip at a depth of 25–30 km where the estimated temperatures are in the only in the 250°–300 °C range (Outerbridge et al., 2010). These results suggest that SSEs can occur at the up-dip transition from the seismogenic zone to the conditionally stable sliding region, and that the lower critical temperature threshold for slow slip is ~250 °C, whereas the upper temperature limit can be as high as 450 °C. The large difference between the flat slab Mexican SSEs and the steep slab Central American SSEs, is likely to be related with the slab thermal structure, amount of fluids released, slab geometry and the length of the conditionally stable slab segment where these events actually take place (Fig. 11).

Another interesting and important characteristic of the SSEs is their correlation with episodes of enhanced NVT activity (Brown et al., 2009; Obara and Hirose, 2006; Payero et al., 2008; Rogers and Dragert, 2003). It is commonly accepted that NVTs and SSEs represent the manifestation of the same process on the transition zone between the seismogenic zone and free-slipping segments along the subduction interface. NVTs are long-lasting, low frequency vibrations located in the vicinity and above the subduction interface, and they are commonly associated with unsteady fluid flow movements (Ito et al., 2007; Shelly et al., 2006). In central Mexico, V.C. Manea and M. Manea (2011) show that the amount and location of fluids released from the subducting Cocos slab correlate with the location of NVT clouds, suggesting that slab dehydration is responsible for triggering the tremors and probably the SSEs (Fig. 11). The flat slab interface temperature for the NVTs in Mexico is ~400–500 °C. However, in Costa Rica, NVTs occurs where the slab interface temperature is only ~200–250 °C suggesting that low-grade metamorphic dehydration reactions might also produce NVTs (Outerbridge et al., 2010).

If NVTs represent the manifestation of fluid–crust interaction, the long-term effect of continental crust hydration and evolution of subduction systems are not yet well understood. Manea and Gurnis (2007) show that large negative pressure (i.e. suction force) above the slab interface is sufficiently high to compensate the slab negative buoyancy, and in some cases, this could sustain long-lived flat-slab subduction systems. Flat slab subduction zones probably represent the best places to study the effects of slab-crust long-term interaction since slab geometry variations (i.e. slab rollback) should induce a clear residual effect on both surface and crust. In Central Mexico geological evidence shows that flat subduction has been going on since the Middle Miocene but that since ~9 Ma the volcanic front migrated trenchward at a rate of ~10 km/Myr (Ferrari, 2004; Ferrari et al., 2012), suggesting slab rollback. In this situation the coupled process of slab dehydration/crust hydration may have eventually weakened the region above the flat-slab but also facilitated the decoupling of

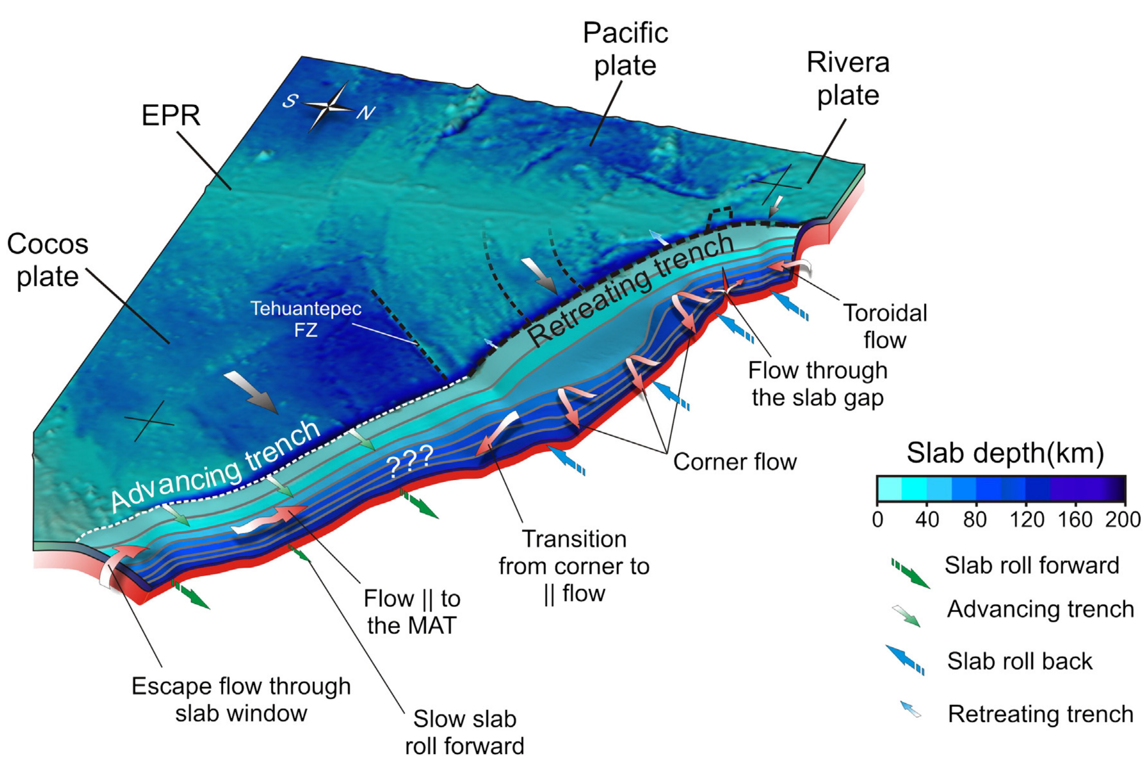

Fig. 12. Mantle wedge flow patterns (based on seismic anisotropy studies referred in the text) along the MASZ beneath the Caribbean and North America plates. The two distinct flow regimes are caused by opposite movement of the MAT (mantle reference frame see Schellart et al., 2008): trench retreat for the northern MAT and trench advance for the southern part of the MAT. Note the slow slab roll forward beneath Costa Rica which creates the trench ward migration of the volcanic arc since Early Miocene (Hoernle et al., 2008).

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subducting and overriding plates, which subsequently resulted in slab rollback (V.C. Manea and M. Manea, 2011).

6.4. Mantle flow along MAT and seismic anisotropy

Anisotropy measurements in subduction zones are commonly used to study the interaction between subducted slabs and mantle flow (Fischer et al., 2000; Hall et al., 2000), with the general assumption that the fast direction of anisotropy tends to align parallel to the mantle flow (Peyton et al., 2001). Several anisotropy studies have found that in general mantle material above (i.e. mantle wedge) and below the highly viscous subducting slabs is flowing parallel to the strike of the trench (Fouch and Fischer, 1996; Mehl et al., 2003; Peyton et al., 2001; Russo and Silver, 1994; Smith et al., 2001; Yang et al., 2009). For example, for the South American subduction zone, the mantle below the Nazca slab flows parallel with the trench (Anderson et al., 2004). This apparently contradictory observation with the eastward motion of the Nazca plate (in the Indo-Atlantic hot-spot reference frame) has been attributed to the slab rollback which would cause a trench parallel astenospheric flow that escape around the northern and southern Nazca slab edges (Russo and Silver, 1994). Along MAZS beneath Costa Rica and Nicaragua, the recent TUCAN seismic experiment revealed a similar mantle anisotropy pattern: fast polarization directions below the Cocos slab, as well as above, are dominated by arc-parallel azimuths (Abt et al., 2010; Hoernle et al., 2008; Rabbel et al., 2011). Beneath central Mexico the fast polarization directions are normal to the MAT and consistent with the Cocos and Rivera plates movement (Rojo Garibaldi, 2012). However, farther south beneath Chiapas a drastic change of the fast polarization direction in the mantle, predicted by Manea and Manea (2006) and recently confirmed by Stubailo et al. (2012), marks the transition between two distinct mantle regimes along MAT. We interpret these two distinctive flow patterns as related with the Cocos and Rivera slab and trench dynamics. In the case of southern MAT, the trench, and subsequently the subducting slab, is advancing eastward (Schellart et al., 2008). In a similar manner as for the South American margin, but with an opposite trench and slab dynamics, the subducting Cocos slab rolls forward and drives laterally the mantle wedge material through the nearby slab window beneath Panama. On the other hand, the Mexican slab and margin, which experienced rollback, created the necessary conditions for a trench perpendicular mantle flow (Fig. 12). Although anisotropy studies can successfully provide proxies for mantle flow directions, they are not able to constrain the actual sense of motion. However, using lead isotope data Hoernle et al. (2008) show that rapid arc-parallel flow towards northwestern Nicaragua occurs in the mantle wedge beneath Costa Rica and Nicaragua. Although the westward migration of the volcanic front since the early Miocene was greatest in Nicaragua, Honduras and El Salvador, suggesting slab rollback, this might not be that case in a hot spot reference frame (Schellart et al., 2008). In this absolute reference frame, the MAT in Central America is actually rolling forward (Fig. 12) and the trenchward migration of the volcanic arc suggests differential slab roll-forward in this region. A better constraint for the mantle flow around the Cocos and Rivera subducting slabs will require time-dependent 3D numeric models of slab dynamics, which include realistic plate and trench reconstructions in the Indo-Atlantic hot spot reference frame.

7. North America, Cocos and Caribbean triple junction

The plate boundaries configuration between the interacting North America, Cocos (Farallon) and Caribbean plates has been evolving since the Early Tertiary. During this time the most remarkable aspect was the southeastward lengthening of the MAT as the transform boundary between the Chortis block and NAM was replaced by a subduction boundary between the NAM and Cocos plate. In Middle to Late Miocene the Chortis block moved east of the Tehuantepec Isthmus and interacts with the easternmost part of the continental NAM plate, the Yucatan block. At present the western tip of the Chortis has almost passed the Yucatan block but the late evolution of the CAR–NAM–Cocos

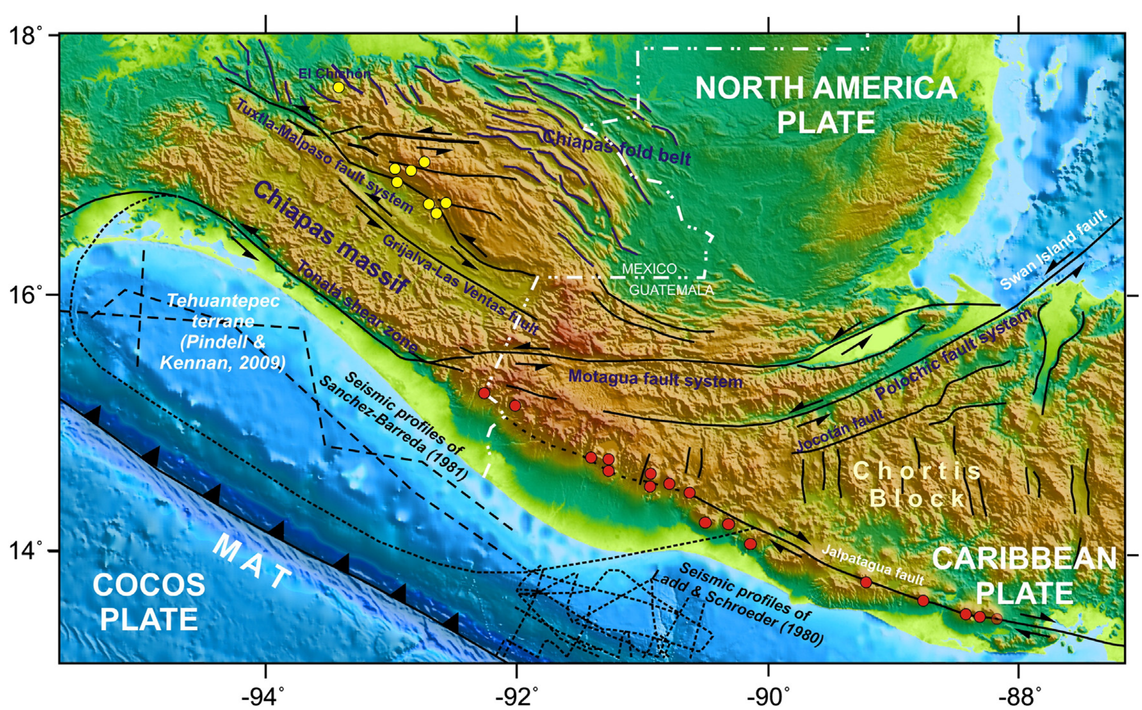

Fig. 13. Tectonic map of the Cocos–North America–Caribbean triple junction region (with structures from Authemayou et al., 2011; Pindell and Kennan, 2009; Witt et al., 2012). Faults in black; fold axis in blue. Red filled dots represent main Late Pliocene–Quaternary volcanic centers. MCVA = Modern Chiapanecan Volcanic Arc.

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triple junction is not well understood. In fact the nature and surface expression of the triple junction is ambiguous. Whereas the active continental North America–Caribbean plate boundary in eastern Guatemala is clearly expressed in the arcuate and subparallel Polochic and Motagua fault zones, its continuation in westernmost Guatemala and southernmost Mexico as well as and the intersection with the MAT is much less obvious (Fig. 13). In the early days of plate tectonics the easternmost NAM–CAR plate boundary was depicted as an ~E–W prolongation of the Motagua fault zones up to the MAT. This kind of triple junction would imply that the transform boundary cut across the continental shelf just offshore western Guatemala and southeastern Mexico and would offset the MAT with time. Seismic lines crossing the continental shelf along the projected trace of the Motagua fault zone offshore Chiapas show no evidence of an E–W fault zone in this region (Sanchez-Barreda, 1981), a fact that led Keppie and Morán-Zenteno (2005) to infer that the plate boundary would rather curve to the south and intersect the MAT offshore Guatemala. Pindell and Kennan (2009) proposed the existence of a forearc block bounded by the Chiapas massif and the MAT, named "Tehuantepec terrane", which would be a remnant of the Caribbean arc that sutured with North America at the end of Cretaceous. In their model the Chortis block would have passed just south of the Tehuantepec terrane so that the NAM–CAR transform boundary would run along an inferred fault with left step to the Motagua fault zone (Fig. 13). A prolongation of the CAR–NAM plate boundary from the Motagua fault zone to the SW up to the MAT, as proposed by Keppie and Morán-Zenteno (2005) and Pindell and Kennan (2009), is difficult to reconcile with the seismic lines presented by Ladd and Schroder (1984) in the frame of the DSDP 84, which show that the forearc offshore Guatemala is also undisturbed since the Paleocene. In addition, the MAT in front of Chiapas or Guatemala show no ~E–W offset, as expected if a simple S–S–T triple junction had been located somewhere along trench. Geodetic data also show that NAM–CAR relative motion decrease from ~20 mm/yr in central Guatemala to ~12 mm toward the Pacific coast (Lyon-Caen et al., 2006), implying that the triple junction become distributed in a wide area characterized by a complex array of structures with variable geometry and kinematics. Deformation on both sides of the Polochic–Motagua fault zone is very different: to the south the CAR plate is under a transtensional regime apparently partitioned in several ~N–S trending grabens in the back-arc region (Gordon and Muehlberger, 1994; Guzmán-Speziale, 2001; Plafker, 1976) and right-lateral intra-arc faulting bounding a narrow, trench parallel, fore arc sliver (Alvarado et al., 2011; Corti et al., 2005; DeMets, 2001; Wunderman and Rose, 1984); to the north the NAM has been affected by a transpressional deformation regime expressed by trench parallel left-lateral strike slip faults (Anderson et al., 1973; Authemayou et al., 2011) and oblique and reverse faults in the Sierra de Chiapas and its buried front (Guzmán-Speziale and Meneses-Rocha, 2000; Witt et al., 2012). This overall deformation pattern is compatible with a northward concave geometry of the left-lateral NAM–CAR boundary. In fact several authors have proposed that the plate boundary may continue from the Motagua fault zone to the west and northwest along several left lateral strike slip faults in western Chiapas (Tuxtla–Malpaso fault system, Tonalá shear zone, Grijalva-Las Ventas fault etc., Fig. 13) (Andreani et al., 2008; Witt et al., 2012) some of which had historical seismicity (Guzmán-Speziale, 2010). The more recent structural studies integrating field observation with seismic reflection and well data agree in considering that after the Miocene the triple junction has become diffuse and propagated to the northwest into the strike slip faults and fold belt of the Sierra de Chiapas (Andreani et al., 2008; Witt et al., 2012), with small blocks of the North American margin dragged into the wake of the eastward escaping Chortis block (Authemayou et al., 2011). In this context Phipps Morgan et al. (2008) propose that the strength of the subducting Cocos plate is a key factor in producing extension in the Caribbean plate and shortening in the North American plate, maintaining a diffuse triple junction.

8. Middle America trench dynamics and Cocos slab geometry

The split of the oceanic Farallon plate into Cocos and Nazca plates at the beginning of the Miocene induced far-reaching consequences in the plate dynamics along MAT. Among these effects, the most important are the less oblique subduction along MAT and the acceleration of EPR spreading, which in mid Miocene reached a world record speed (Wilson, 1996). Lallemand et al. (2005) show that slab dip decreases for faster net convergence between the subducting plate and upper plate, and therefore a reduction in slab dip along MAT should be expected during the mid Miocene super-fast spreading period. As we show in Fig. 5, the flat-slab onset in central Mexico does correlate with this period, however in Central America the CAVA has experienced only a modest trenchward displacement since the Miocene, suggesting that slab flattening did not occur here. The statistical treatment of Lallemand et al. (2005) shows that ~40% of slabs with advancing upper plates have dips that are lower than the mean slab dip, whereas ~80% of slabs with retreating upper plates have dips that are steeper than the mean. Along MAT, the NAM and Caribbean overriding plates are characterized by these two contrasting upper plate regimes. While the NAM plate in Mexico advances with 1–2 cm/yr westward, the Caribbean plate has been stationary for the last 40 Ma (Müller et al., 1999), although being trapped between three large tectonic plates its tectonic boundaries accommodate significant deformation. The trench movement is generally consistent with the overriding plate kinematic, nevertheless it is affected by subduction erosion and shortening (McIntosh et al., 1993). Manea et al. (2012) demonstrate that trench dynamics has an important effect on slab dip variations along the Andes. They show that a stationary trench coupled with an advancing overriding plate (in the Indo-Atlantic hot spot reference frame, O'Neill et al., 2005) favors an increased slab dip, while a trench rollback is the necessary condition for slab shallowing. Along the northern MAT the trench perpendicular migration velocity varies from ~1 cm/yr offshore western Mexico to ~0.4 cm/yr in southern Mexico. On the other hand the southern MAT the trench rolls forward at nearly ~−2 cm/yr (Schellart et al., 2007). When combining the contrasting trench kinematic along MAT with the super-fast EPR spreading event in mid Miocene, a picture of an intrinsic connection with the dramatic slab dip variations along MAT emerges. The onset of flat slab in central Mexico is caused primarily by the superposition of two causes: the acceleration of EPR spreading at rates above 15 cm/yr and the trench rollback and the advancing of overriding plate. In the same time, the even superior EPR acceleration farther south (~20 cm/yr) was not able to induce any considerable slab shallowing or even flattening due to the Caribbean plate dynamics coupled with trench retreat. A model of kinematic evolution of Cocos slab geometry along MAT since Early Miocene is presented in Fig. 14.

9. Conclusions: future geodynamical studies of the MASZ

In this paper we have reviewed the principal geological, geophysical and tectonic processes along the Mexican and Central America subduction zones, and provide for the first time an integrated geodynamical perspective on the first order effects regarding the interaction between the subducting Rivera and Cocos slabs and the North America and Caribbean plates. The results from recent large-scale experiments along this margin have been presented and discussed. Integration of regional geology, volcanism, tectonics, seismicity and crustal deformations along the MASZ provided us a strong connection between deep geodynamic processes and their manifestation on the surface. Based on this solid observational foundation we then incorporate these results into a coherent geodynamical

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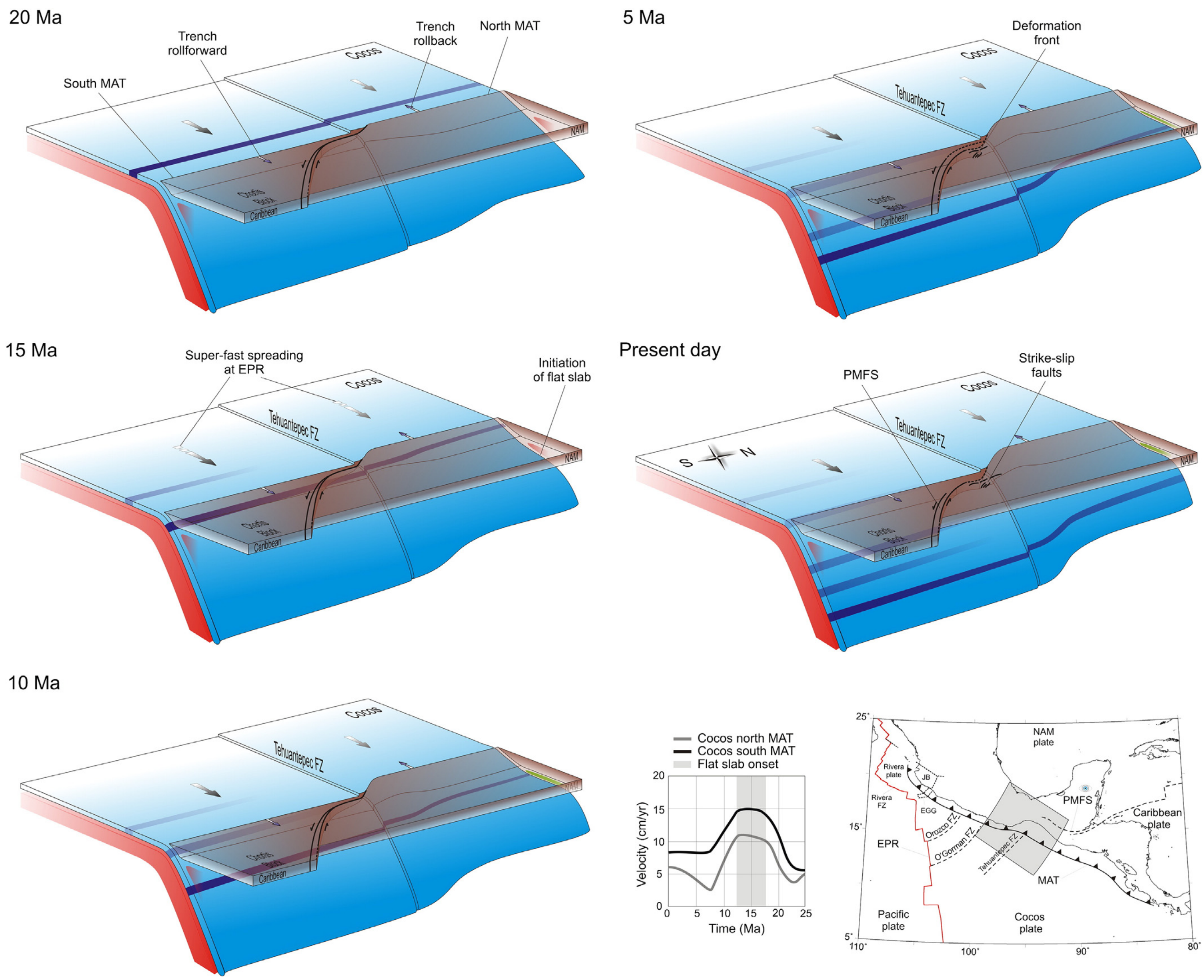

Fig. 14. Kinematic model (mantle reference frame) of the subducting Cocos slab along the MAT in the vicinity of Cocos–Caribbe–North America triple junction since Early Miocene. The evolution of Caribbean–North America tectonic contact is based on the model of Witt et al. (2012). The blue strips represent markers on the Cocos plate. Inset shows the convergence velocity of the Cocos plate to the north and to the south of the Caribbean–North America boundary based on Sdrolias and Muller (2006). Note how trench roll forward is associated with steep slab in Central America, whereas trench roll back is associated with flat slab in Mexico.

framework, and shed light on the main processes controlling the subduction system evolution in this region.

In this last section we highlight briefly the main geodynamic scenarios proposed in this paper, with the main purpose to provide a coherent starting base for future geodynamical modeling studies tailored to the Middle America Subduction Zone.

The configuration of the subducting Rivera and Cocos plates along the MASZ show significant variations along the strike, from very steep subduction in western Mexico, to shallow flat slab subduction in central Mexico, and then steep subduction beneath Central America. The explanation for such a remarkable contortioned geometry should be the primary goal for forthcoming numerical models. Based on considerable knowledge of this active margin accumulated during the last decade and reviewed in this paper, our testing hypothesis is that a combination of subduction parameters such as, convergence rates, trench dynamics and plate age has the real potential to explain this first order observation.

Significant variations in convergence rates and direction between the Rivera and Cocos plates since ~10 my are proposed to be responsible for the slab discontinuity (i.e. slab gaps) revealed recently by the MARS seismic experiment. Slab rollback, toroidal flow around the Rivera slab edge and a proposed incipient intra-arc spreading in the Tampic–Zacolalco rift, represent another set of processes that need to be validated by time-dependent realistic geodynamic models.

The remarkable phenomenon of flat slab subduction of the Cocos plate beneath central Mexico is still an open issue for the scientific community. Also, the two volcanic gaps that bound laterally, and apparently related with, the flat slab subduction in Mexico, do not have an easy explanation so far. Although several hypotheses and scenarios have been proposed here, we are in the need of a well-constrained, realistic 3D time-dependent numerical model that is able to explain the apparently contradictory observations in this region.

The detachment of the lower part of the slab during the Late Miocene is another remarkable process at the MASZ that is now consistently supported by geologic evidences, seismic tomography, and observed variation of geodynamic parameters. However, the details of the time–space evolution of this process as well as the influence in the petrogenesis of the arcs are not completely understood and deserve to be studied by thermochemical and petrologic modeling.

Although some progress has been made in deciphering the actual position and dynamics of the Cocos–Caribbean–North America triple junction, the implications of southeastward lateral migration of this

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triple junction, including the Chortis block, remain open. Slab dip geometry variations, crustal movement, arc migration and long-term perturbations in the mantle flow, are only few examples of the issues that need to be addressed in future studies.

The recently discovered SSEs and NVTs along the MASZ show that we are still far from understanding subduction processes, even at a short time scale. Analyzing in details and comparatively these signals in regions where slab geometry is at the two extremes (i.e. very steep beneath western Mexico and Central America, and perfectly flat beneath central Mexico), could offer us a unique opportunity to differentiate among the proposed mechanisms that is responsible for these observations.

Seismic observations along MASZ are too insufficient to allow a well-defined configuration of seismic anisotropy along the entire margin. Although recent studies point to the asthenospheric flow as the actual mechanism responsible for the observed anisotropy, the specific observed anisotropy pattern around the Rivera and Cocos slabs is not yet well understood. Future high-resolution geodynamic modeling for the entire Mexican and Central American subduction systems can provide the missing link in better understanding the seismic anisotropy and mantle dynamics, and in particular the evolution of MASZ as a whole.

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