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Middle to Late Miocene Contractional Deformation in Costa Rica Triggered by Plate Geodynamics

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Key Points:

- A widespread middle to late Miocene contractional deformation event took place in Costa Rica
- Contraction in a subduction setting triggered by the onset of orthogonal convergence between the Cocos and Caribbean plates

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Abstract Contractional deformation in Costa Rica is usually attributed to the subduction of the aseismic Cocos Ridge. In this work, we review the evidences for contraction in the middle to late Miocene, prior to the arrival of the Cocos Ridge at the Middle America Trench. We find that the Miocene phase of contractional deformation is found in all of Costa Rica, probably extending to Nicaragua as well. The widespread distribution of this event requires a regional or plate geodynamic trigger. We analyze the possible mechanisms that could produce the onset of contractional deformation, using the better known case of subduction orogeny, the Andes, as an analog. We propose that a change in the direction of the Cocos plate since ~19 Ma led to a change from oblique to orthogonal convergence, producing contractional deformation of the upper plate.

1. Introduction

Most works attribute the onset of contractional deformation and uplift in Costa Rica to the subduction of the aseismic Cocos Ridge (Montero, 2000; Morell, 2015, 2016), which would have resulted in the development of a flat-slab segment (Fisher et al., 2004; Morell, 2016). In this scenario, slab flattening could explain the gap in arc magmatism between Turrialba volcano to the north and Barú volcano in Panama to the south (Abratis & Wörner, 2001; de Boer et al., 1995; for an alternative view on the origin of this gap see Morell, 2015) and the uplift of the Cordillera de Talamanca and the Fila Costeña thrust belt (Figure 1) (Kolarsky et al., 1995; Morell, 2015, 2016; Morell et al., 2012; Sitchler et al., 2007). However, both the age of arrival of the Cocos Ridge at the Middle America trench, which is estimated from 0.5 Ma (Gardner et al., 1992; Protti et al., 1995) to 8 Ma (Abratis & Wörner, 2001), and the effects of this event on the subduction system (Dzierma et al., 2011, 2010; Lücke & Arroyo, 2015; Morell, 2015) are matters of debate.

While many researchers have suggested an older event of deformation during the middle to late Miocene (e.g., Astorga et al., 1991; Denyer & Arias, 1991; Gursky, 1988; MacMillan et al., 2004; Weyl, 1957), prior to the arrival of the Cocos Ridge to the trench, the tectonic significance of this event has been largely ignored in many studies. In this contribution, we summarize the evidence for this Miocene contractional event and discuss possible triggers for its onset, contributing to the knowledge of the behavior of subduction systems and the controls on subduction-related orogenesis.

2. Geologic Setting

In Costa Rica, the Oligocene and early Miocene are characterized by sedimentation in submarine basins (Figure 1b) ranging from turbidites to shallow marine rocks. Two different basin domains were located along the Pacific and Atlantic slopes. The magmatic arc was characterized by two different volcanic belts in northern Costa Rica, the Aguacate and Sarapiquí arcs, shown as Miocene-Pliocene igneous rocks in Figure 1 (Gazel et al., 2005, 2009). In the south, a single arc located in the current Talamanca range was developed (Gazel et al., 2009). It is usually considered that some of the volcanos of these arcs were islands (e.g., Alvarado et al., 2007), and continental deposits indicating the emergence of the Central American isthmus have only accumulated in Costa Rican basins since the latest Miocene or early Pliocene (Denyer et al., 2000; Linkimer & Aguilar, 2000). Some researchers propose that early to middle Miocene basin development

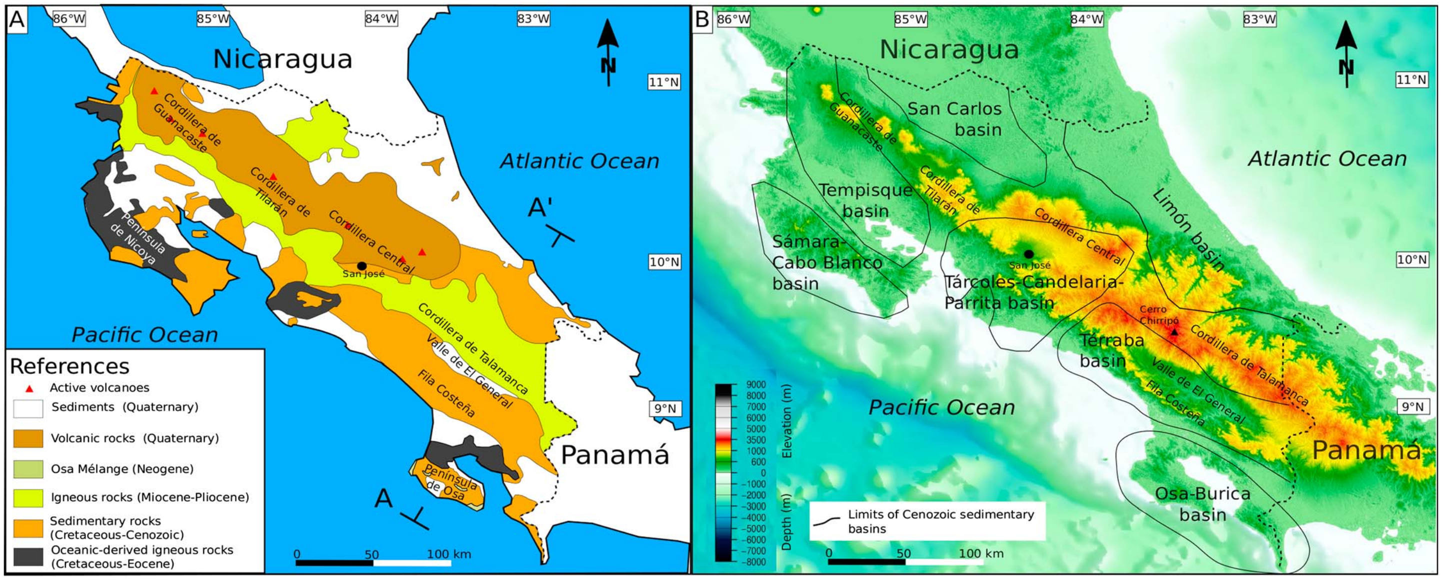

Figure 1. (a) Simplified geologic map of Costa Rica (based on Tournon & Alvarado, 1995 and Denyer & Kussmaul, 2000). A-A′ indicates the location of the cross section in Figure 3. (b) Topographic and bathymetric map of Costa Rica (data from Shuttle Radar Topography Mission, NASA, and ETOPO1, NOAA). The limits of Cenozoic basins are also shown.

occurred under an extensional tectonic regime (e.g., Denyer & Arias, 1991), while others indicate a transtensional setting (e.g., Astorga et al., 1991).

The present geologic setting is characterized by a number of volcanic ridges subparallel to the trench in northern Costa Rica (Figure 1a), including the Guanacaste and Central Cordilleras, which are straddled by active volcanoes. In southern Costa Rica, the Cordillera de Talamanca reaches an altitude of 3,820 m above sea level at Cerro Chirripó (Figure 1b). This range, in which there is no Quaternary volcanic activity, is composed mainly of late Miocene calc-alkaline intrusive rocks with subordinate volcanics of the same age (Kussmaul, 2000; Morell et al., 2012). The southwest vergent Fila Costeña thrust belt, developed to the southwest of the Cordillera de Talamanca (Figure 1), deforms the Eocene to Miocene sedimentary succession of the Térraba basin and younger rocks including Quaternary sediments and has been suggested to accommodate 36 km of shortening since the middle Pliocene (Sitchler et al., 2007).

3. Tectonic Reconstructions and the Subduction System of the Middle America Trench

The subduction system in southern Central America had a very complex evolution in the Cenozoic. The plate margin experienced the subduction of oceanic lithosphere from different spreading centers, as well as seamounts, ridges, and fracture zones (Barckhausen et al., 2001; Lonsdale, 2005; MacMillan et al., 2004; Morell, 2016).

The Paleogene was characterized by the subduction of the Farallon plate below the Caribbean plate along the Middle America trench. Until ~26 Ma, movement of the Farallon plate was toward the east at the latitude of Central America, oblique to the Costa Rica segment of the trench (Barckhausen et al., 2008; Lonsdale, 2005; Müller et al., 2016). At the Oligocene-Miocene boundary (~25 Ma), the Farallon plate broke up into the Nazca and Cocos plates (Hey, 1977; Lonsdale, 2005; Meschede & Barckhausen, 2000). Between 25 Ma and the present, the southern limit between the Cocos and Nazca plates changed with the development of three subsequent Cocos-Nazca spreading centers (CNS): CNS-1, which was active between 25 and 19.5 Ma (Figure 2); CNS-2, which was active between 19.5 and 14.7 Ma; and CNS-3, which was active from 14.7 Ma to the present (Meschede et al., 1998). The eastern limit between the Cocos and Nazca plates is presently marked by the Panama fracture zone, which subducts at the Costa Rica-Panama border (Figure 2). The Coiba fracture zone, which is subparallel to the Panama fracture zone, may have been the plate limit in the past (MacMillan et al., 2004). The latest reconstructions (MacMillan et al., 2004; Morell, 2015) indicate that these fracture zones

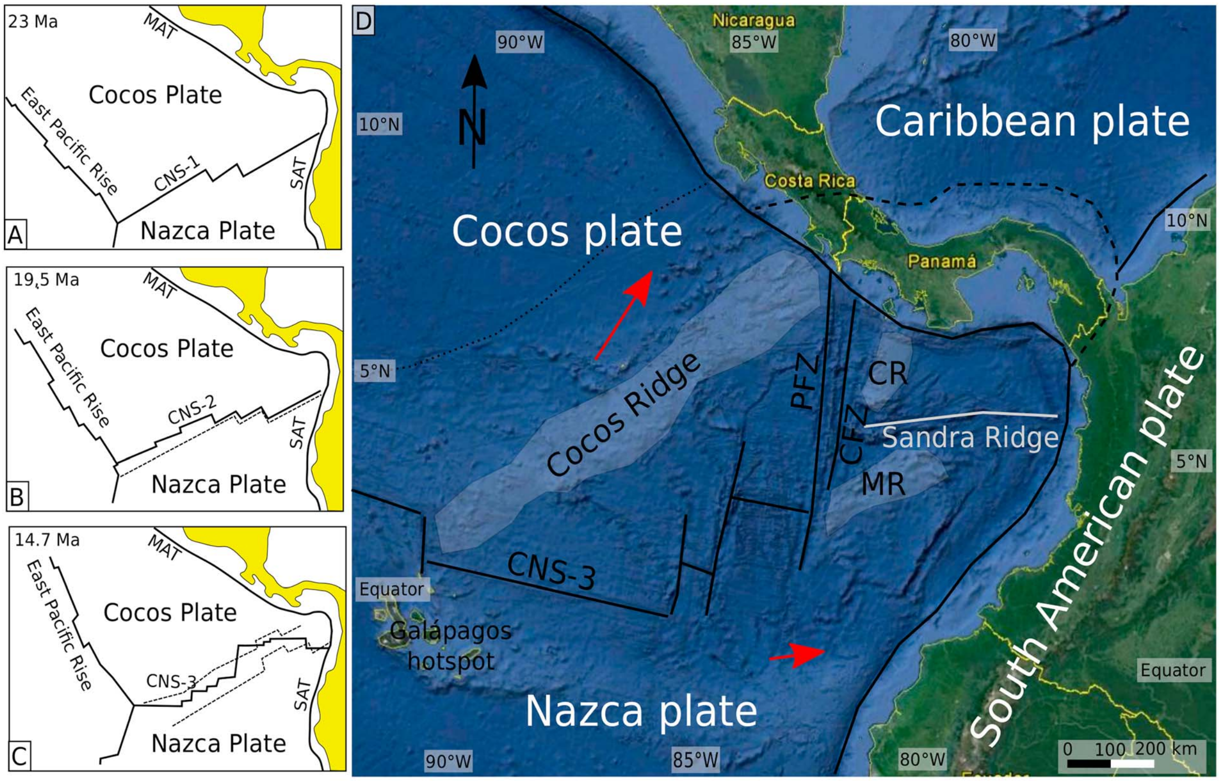

Figure 2. Central America tectonic setting. (a–c) Evolution of the spreading ridges bounding the Cocos plate throughout the Neogene (based on Meschede & Barckhausen, 2000). Dashed lines in Figures 2b and 2c indicate inactive (abandoned) spreading centers. MAT: Middle America Trench, SAT: South American Trench. (d) Present configuration showing the main features of the oceanic plates, over Google Earth image. The pointed line is the limit between East Pacific Rise-derived crust and CNS-derived crust. The dashed line indicates the approximate limits of the Panama microplate proposed by Astorga et al. (1991). PFZ: Panama fracture zone, CFZ: Coiba fracture zone, CR: Coiba ridge, MR: Malpelo ridge. Red arrows indicate convergence direction and velocity. Figure 2d is based on Morell (2015, and references therein).

developed since 8 Ma, leading to the formation of the Panama triple junction. Before that, only the Cocos plate subducted below the Middle America trench (Morell, 2015). The development of the Panama triple junction had important implications for the subduction system, namely, determining the capture of the eastern part of the Cocos plate by the Nazca plate. Therefore, since 8 Ma, subduction at the Middle America trench is divided into a western sector of nearly orthogonal convergence with Cocos plate subduction and an eastern sector of highly oblique Nazca plate subduction (Figure 2).

The subduction characteristics are further complicated by the variations of thickness and topography of the Cocos plate. Three domains of oceanic Cocos crust are recognized from west to east (Figure 2): a sector with smooth oceanic crust derived from the East Pacific Rise (the spreading center in the middle of the Pacific ocean), a sector with rough crust characterized by a rugged topography derived from the Cocos-Nazca spreading centers, and finally, the Cocos Ridge, an aseismic, mostly submarine, mountain chain derived from the Galápagos hot spot (Meschede et al., 1998; Protti et al., 1994), which is 2,000 m higher than the average ocean floor and has a crustal thickness of 20 km along its axis (Walther, 2003). Minor ridges, such as the Coiba and Malpelo ridges, are also present in the Nazca plate (Figure 2).

3.1. Subduction of the Cocos Ridge

The onset of subduction of the Cocos Ridge has been variably estimated from 8 Ma to 0.5 Ma, based on different methods. Oldest estimates are based on the interpretation of upper plate processes produced by ridge subduction. Abratis and Wörner (2001) suggested that eruption of back-arc basalts with adakitic signature at 5.8 Ma was the result of a slab window produced by the subduction of the buoyant Cocos Ridge at 8 Ma. Subduction of the ridge at 5 Ma was proposed by de Boer et al. (1995) based on a regional unconformity and the cessation of volcanic activity in the Cordillera de Talamanca at 3.5 Ma. Meschede et al.

(1999) proposed that the ridge subducted since 5–4 Ma producing uplift of marine terraces and exhumation of the subduction channel (Osa mélange) in the Osa Peninsula. In contrast, more recent reconstructions of the evolution of the Cocos and Nazca plates indicate that the Cocos Ridge could not have reached the trench before 3 Ma (MacMillan et al., 2004; Morell, 2015). Some authors propose even younger ages of 0.5 Ma based on elastic deformation modeling (Gardner et al., 1992; Protti et al., 1995). Oceanic plate reconstructions (MacMillan et al., 2004; Morell, 2015) are a more precise method to calculate the age of ridge subduction—even taking into account the uncertainties in these reconstructions, the interpretation of upper plate processes is more speculative and other explanations have been proposed for the unconformities, the cessation of magmatism, and adakitic basalts (see MacMillan et al., 2004 and Morell, 2015 for a discussion). A young age of Cocos Ridge subduction is therefore favored, starting at 3–2 Ma or less. In any case, even the oldest estimates of 8 Ma postdate the onset of Miocene deformation, as described in the following.

4. Evidence for Miocene Contractional Deformation Prior to the Subduction of the Cocos Ridge

4.1. Cordillera Central

The Cordillera Central region is characterized by Paleogene to Miocene sedimentary and volcaniclastic successions (Pacacua, Peña Negra, and Coris Formations and equivalent units), deposited in the forearc Candelaria basin (Figure 1), which are affected by folding, thrusts, and strike-slip faults (Denyer & Arias, 1991). These rocks are overlain by the arc-related volcanic rocks of the Aguacate Group (Denyer & Arias, 1991), composed of basaltic to andesitic lavas, tuffs, and lahar deposits (Dengo, 1962; Denyer & Arias, 1991; Marshall et al., 2003). The Aguacate Group is divided in two units. The lower La Cruz Formation, dated by $^{40}Ar/^{39}Ar$ thermochronology to ~11 Ma (Gazel et al., 2009; MacMillan et al., 2004), is deformed in conformity with lower units and unconformably covered by the undeformed, flat-lying Grifo Alto Formation (Denyer & Arias, 1991). Lava flows from the Grifo Alto Formation have been dated by $^{40}Ar/^{39}Ar$ thermochronology to 7.3 to 2 Ma (Alvarado & Gans, 2012; Gazel et al., 2009; Marshall & Idleman, 1999). Important geochemical variations between both units of the Aguacate Group have been reported (Alvarado & Gans, 2012; Bellon & Tournon, 1978; Marshall et al., 2003). The chemistry of the volcanic rocks of the Aguacate Group shows an evolution from an island arc signature (La Cruz Formation) to a mature continental arc composition in the Grifo Alto Formation, reflecting crustal thickening during the Miocene (Gazel et al., 2005). Therefore, the unconformity between the La Cruz and Grifo Alto Formations indicates a period of contractional deformation in the late Miocene, as already recognized by MacMillan et al. (2004). The $^{40}Ar/^{39}Ar$ ages currently available constrain this deformation event between 11 and 7,3 Ma.

4.2. Fila Costeña and Cordillera de Talamanca

Some authors propose a Pliocene onset of contraction in the Fila Costeña (Figure 1) (Sitchler et al., 2007), based on a report indicating that an unnamed Pliocene mudstone unit rests unconformably on late Miocene sandstones and conglomerates (Curré Formation; Kesel, 1983). This has been interpreted as the record of a Pliocene marine inundation predating deformation and uplift. However, the unconformity between these two units indicates that the Fila Costeña thrust belt was also deformed earlier, before a Pliocene subsidence event allowed the deposition of the mudstones. In contrast, compelling evidence of a Miocene event of contraction is given by the syntectonic nature of the gabbroic sills of the 15 to 11 Ma Puerto Nuevo Formation (Alvarado & Gans, 2012; MacMillan et al., 2004). The intrusion of this unit was mostly controlled by thrust faults of the Fila Costeña, and in turn some of the intrusions cut the faults with minor or no displacement (Figure 3a) (Kolarsky et al., 1995).

Deformation in the Fila Costeña was probably linked to deformation and uplift in the Cordillera de Talamanca. Many authors have proposed that thrusts in the Fila Costeña root in a detachment level that connects with a major reverse fault that uplifted the Cordillera de Talamanca (Figure 3c) (Fisher et al., 2004; Morell, 2016; Sitchler et al., 2007). This configuration is likely for all deformation events in the Fila Costeña, suggesting that the Cordillera de Talamanca was also uplifted in the middle to late Miocene event. Accordingly, the unconformity between Miocene sedimentary rocks and the Grifo Alto Formation and equivalent volcanic rocks is also found in the Cordillera de Talamanca (Figure 3b).

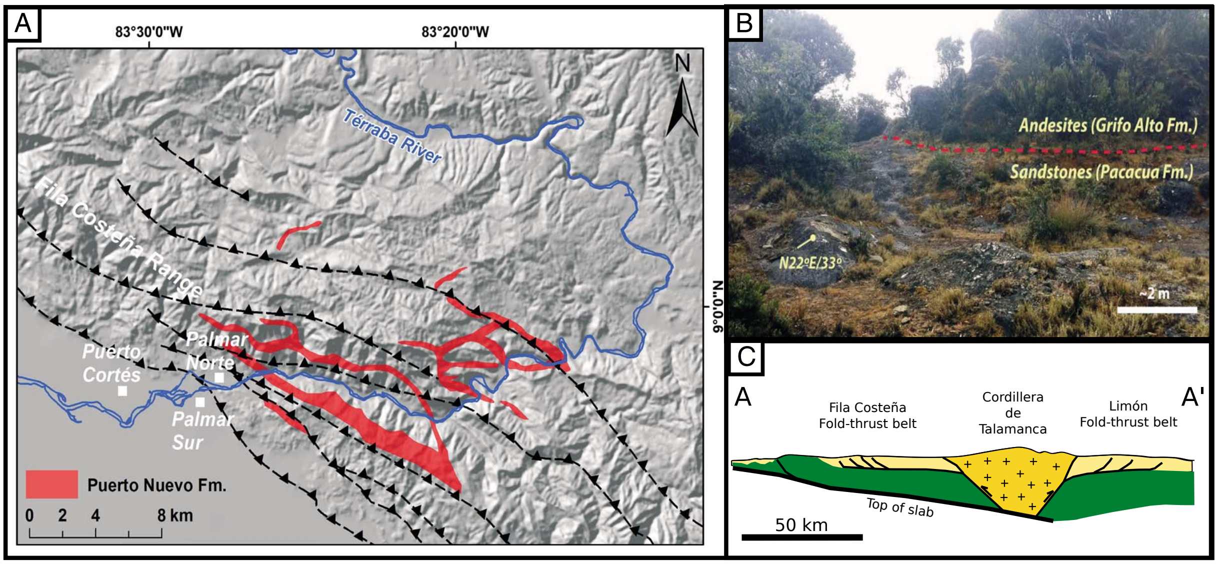

Figure 3. Miocene deformation in the Fila Costeña and Cordillera de Talamanca. (a) Map showing the relationship between the gabbroic intrusions of the Puerto Nuevo formation and the thrusts in the Fila Costeña (from Denyer & Alvarado, 2007) over a shaded relief map derived from Shuttle Radar Topography Mission data (SRTM digital elevation model). (b) Unconformity between the Miocene sandstones of the Pacacua formation and the andesites of the Grifo Alto formation in the Cordillera de Talamanca. Location: Cerro Buenavista, 9°33′16″N/83°45′16″W. Altitude: 3,450 m. (c) Schematic cross section A-A′ across southern Costa Rica (location in Figure 1). Cretaceous basement in green, Miocene plutons and volcanic rocks of the Cordillera de Talamanca indicated with crosses, undifferentiated Cenozoic sedimentary rocks of the Térraba and Limón basins in yellow. Note the link between thrusts in the Fila Costeña and the fault that uplifts the Cordillera de Talamanca. From Fisher et al. (2004) and Morell (2016).

4.3. South Limón Basin

The Cenozoic retroarc Limón basin (Figure 1) is inverted in its southern sector, known as the Limón fold and thrust belt. Studies by RECOPE, the Costa Rican state-owned oil company, have obtained seismic data from this fold and thrust belt. Basin inversion is characterized by asymmetric hanging wall anticlines and large southwest dipping listric or planar thrusts. Thrusts located in a more internal position within the fold and thrust belt are generally steeper and have greater offsets than the more external and probably younger thrusts (Brandes et al., 2007, 2008).

Brandes et al. (2007, 2008) document two stages of contractional deformation: the first took place between the late Eocene and the early Miocene and the second in the middle to late Miocene and Pliocene, as recorded in seismic images of the Moín high.

4.4. San Carlos Basin

The San Carlos basin is an extensional intra-arc basin located in northern Costa Rica (Astorga et al., 1991) (Figure 1). Seismic data were analyzed in a number of studies (Astorga et al., 1991; Ballestero et al., 1995; Barboza et al., 1995). Basin subsidence is linked to normal listric faulting with rollover structures and NW-SE trends, aligned to the Nicaraguan depression. The basin fill is related to a Miocene deltaic system.

A postdepositional complex pattern of reverse faulting and folding with dominant E-W strike was developed during the early Pliocene (Astorga et al., 1991; Barboza et al., 1995; Gazel et al., 2005). Ballestero et al. (1995) indicate that the tectonism that deformed the strata was probably recurrent during the late Neogene, with the most recent episode occurring in the late Pliocene.

4.5. Nicoya Peninsula

A contractional event took place in the Nicoya Peninsula during the late Miocene, named the "D4 phase" by Gursky (1988). This event produced folds and reverse faults with WNW trends. The history of the Nicoya peninsula records a complex history of uplift and subsidence events (Seyfried et al., 1991), likely a result of the interplay between regional tectonic processes and the seismic cycle of the subduction zone. Some authors attribute the main folding and tilting, with associated uplift of the Peninsula, to a Eocene event

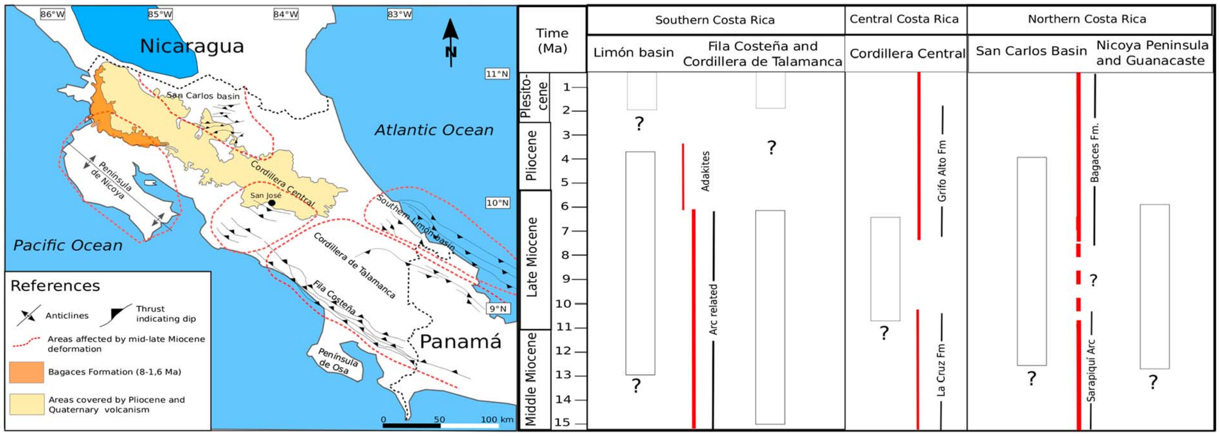

Figure 4. Summary of middle to late Miocene deformation in Costa Rica. Map shows the areas affected by this deformation phase and the main structures developed (based on Gursky, 1988; Denyer & Alvarado, 2007; Morell, 2016, and our own observations). Note that only the northeastern sector of Costa Rica was not affected. Also shown are outcrops of the Bagaces formation, which reflects crustal thickening in the arc region of northern Costa Rica, and the sector covered by Pliocene to Quaternary volcanic rocks that likely conceal Miocene structures (both units based on Denyer & Alvarado, 2007). Diagram on the right shows timing of deformation in each region, as well as periods of magmatic activity (red lines). Question marks indicate periods in which it is uncertain if contractional deformation/volcanic activity took place.

(Baumgartner et al., 1984; Denyer et al., 2014). The importance of the late Miocene deformation is pointed out by Gursky (1988), who attributes the development of the Nicoya anticlinorium, which determined the outline and morphology of the Peninsula, to this event. Astorga et al. (1991) support this view, adding that Miocene deformation was likely a regional event. According to Denyer et al. (2014), the late Miocene and Pliocene silicic ignimbrites of the Bagaces Formation (8–1.6 Ma, Gillot et al., 1994) indicate an evolved and thickened crust during this period, which suggests that the crust in the arc of the Guanacaste region, north of the Nicoya Peninsula, currently covered by Quaternary volcanic rocks (Figures 1 and 4), may also have been thickened by contractional deformation at this time. Gillot et al. (1994) indicate that uplift since 8 Ma was not significant because the Bagaces ignimbrites are not affected by deformation; however, lavas between 6 and 8 Ma are tilted suggesting that some deformation might have taken place during initial Bagaces Formation volcanism (Alvarado & Gans, 2012).

4.6. Summary of Middle to Late Miocene Deformation in Costa Rica

The compilation of pre-Pliocene contractional deformation in Costa Rica shows that most of the country was affected by a middle to late Miocene event of contractional deformation (Table 1 and Figure 4). In most regions, chronological constraints are not good enough to precisely determine the timing of this event. The onset of contraction is well documented at ~15 Ma in the Fila Costeña thrust belt, based on the age of syntectonic sills (MacMillan et al., 2004), and as old as 11 Ma in the Cordillera Central, although this age is

Table 1
Summary of Ages of Middle and Late Miocene Contractional Deformation in Costa Rica

Region	Age of deformation	Constraints	References
Cordillera Central	11 to 7.3 Ma	Ages of deformed and undeformed volcanic rocks	Denyer and Arias (1991), Marshall and Idleman (1999), MacMillan et al. (2004), Gazel et al. (2005, 2009), and Alvarado and Gans (2012)
Fila Costeña and Cordillera de Talamanca	15 to 7 Ma	Age of syntectonic sills in the Fila Costeña, unconformity between deformed and undeformed rocks in the Cordillera de Talamanca	Kolarsky et al. (1995), MacMillan et al. (2004), and Alvarado and Gans (2012)
Limón basin	Middle Miocene to Pliocene	Seismic data	Brandes et al. (2007, 2008)
San Carlos basin	Neogene	Seismic data	Ballestero et al. (1995)
Guanacaste and Península de Nicoya	Late Miocene, until 6 Ma	Structures covered by Pliocene rocks in the Nicoya Peninsula, tilted Miocene ignimbrites (8–6 Ma) in Guanacaste	Gursky (1988), Astorga et al. (1991), Gillot et al. (1994), Alvarado and Gans (2012), and Denyer et al. (2014)

poorly constrained. By ~7 Ma, deformation had ended in the Cordillera Central (Alvarado & Gans, 2012; MacMillan et al., 2004). A middle to late Miocene contractional event has also been suggested for the Limón basin, preceded by a late Paleogene event (Brandes et al., 2007). According to Ballestero et al. (1995), contraction in the San Carlos basin was recurrent during the late Neogene, although precise constraints are lacking. In the Nicoya Peninsula and Guanacaste, a late Miocene contractional phase has been widely documented, with deformation waning since 8 Ma (Alvarado & Gans, 2012; Gillot et al., 1994; Gursky, 1988).

Most structures developed during the Miocene deformation have NW to WNW trends (Figure 4), subparallel to the Middle America trench and perpendicular to the convergence direction. This suggests that the convergence direction determined the compressional stress field in which the structures developed. The major exception to this is the San Carlos basin, where thrusts have E-W trends. This could be the result of a local rotation of stress or of the reactivation of preexisting structures.

Based on the available data, the period between 11 and 8 Ma is a time of widespread contraction throughout Costa Rica (Figure 4b). However, the onset and end of contraction was not coeval in all regions. Locally, the deformation was likely controlled by the features of the upper plate, resulting in temporal variations within the regional contractional deformation phase. When more precise constraints are obtained, it will be possible to analyze this topic in more detail.

5. What Triggered Contractional Deformation in Costa Rica?

5.1. Contractional Deformation in Subduction Systems: The Andes as an Analog

In ocean-continent subduction systems, upper plate contraction can be triggered by several processes, some of which modify the boundary conditions of the system, and others which lead to weakening of the upper plate, facilitating deformation without changing the stress regime. These processes include (i) a high trenchward absolute velocity of the upper plate, which can result in effective overriding of the trench by the upper plate (Forsyth & Uyeda, 1975; Heuret & Lallemand, 2005; Somoza & Zaffarana, 2008); (ii) the inception of orthogonal convergence (Ramos, 1999; Somoza & Zaffarana, 2008); (iii) flat or low-angle subduction, often invoked as the result of the subduction of ridges on the oceanic plate (Cloos, 1993; Ramos & Folguera, 2009); (iv) high interplate shear stresses along the subduction zone, related to a low sediment supply to the trench and ultimately to arid climates (Lamb & Davis, 2003); (v) the age of the subducted oceanic lithosphere, either old (Yáñez and Cembrano, 2004) or young (Protti et al., 1994), which has been proposed to increase plate coupling; and (vi) increased magmatic activity in the arc, leading to thermal weakening of the crust (Kusznir & Park, 1982).

Many works have considered the relative importance of these factors taking the Andes of South America as a natural laboratory. The Andean orogenic belt is the result of crustal shortening produced in the framework of long-lived subduction of the oceanic Farallon and Nazca plates below the continental South American plate (Dewey & Bird, 1970; Oncken et al., 2006). We will use the Andes as an example of subduction-related upper plate contraction to evaluate the possible triggers for upper plate contraction in Costa Rica.

There has been growing consensus in recent years that the absolute velocity of the upper plate is the dominant control on orogenic development in the Andes (Heuret & Lallemand, 2005; Oncken et al., 2006; Ramos, 2010). In this framework, the onset of contractional deformation in the Late Cretaceous is interpreted as the result of a plate reorganization event which led to a high westward velocity of the South American plate (Somoza & Zaffarana, 2008). Cretaceous deformation and uplift was a continental-scale event recognized throughout the different segments of the Andes (Mpodozis & Ramos, 1989).

However, in many segments, the main phase of deformation took place in the Miocene, which indicates that the intensity of deformation in each Andean segment was largely controlled by variations in the convergence direction and velocity, with orogenic development favored by orthogonal convergence (Figure 5) (Ramos, 1999). Before the Oligocene, the convergence direction was dominantly NE (Somoza & Ghidella, 2005) leading to orthogonal convergence in Perú where the margin trends NW, with the consequent development of the Eocene-early Oligocene Incaic orogeny (Steinmann, 1929). Oblique convergence in the rest of the South American margin led to strike-slip tectonics (e.g., Aragón et al., 2011). Since 25 Ma, after the breakup of the Farallon plate (Lonsdale, 2005), the convergence vector changed to E-W (Pardo-Casas & Molnar, 1987;

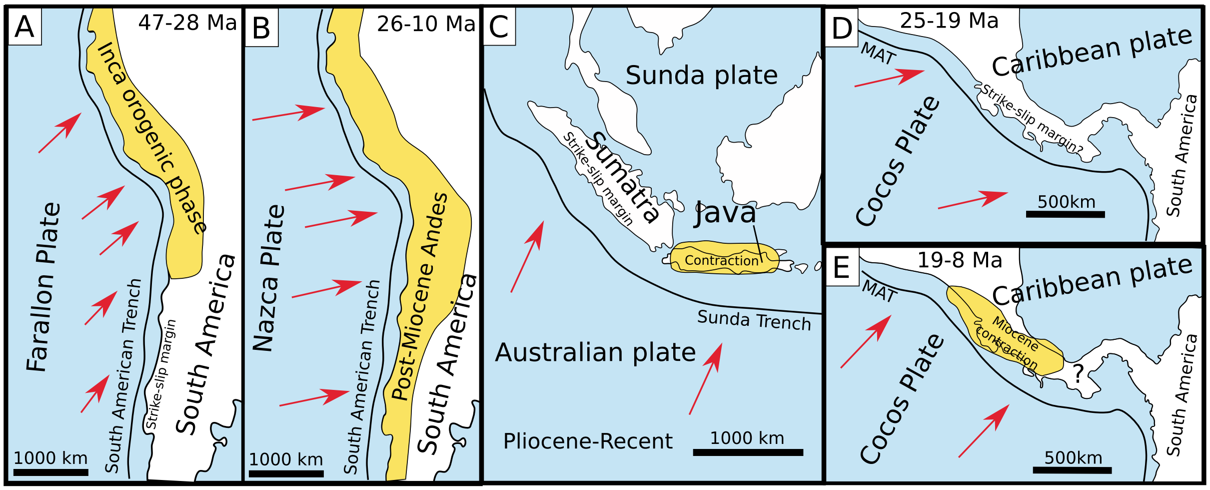

Figure 5. (a) Northeast directed convergence (red arrows) between 47 and 28 Ma in the South American margin. Convergence was oblique to the margin in the southern sector and orthogonal or high-angle in the northern Central Andes, where the Incaic orogenic phase took place. (b) Post-26 Ma eastward convergence and development of the Andes in the Miocene. Convergence directions in Figures 5a and 5b are from Somoza and Ghidella (2005). (c) Convergence between the Indian and Eurasian plates in the Sunda arc. Low-angle convergence in the north leads to a strike slip setting, whereas high-angle convergence in the south produces contractional deformation. Based on Clements et al. (2009) and McCaffrey (2009). (d) Oblique convergence in Central America between 23 and 18 Ma, leading to the development of a strike-slip margin. (e) Orthogonal convergence between 17 and 8 Ma and middle to late Miocene contraction.

Somoza & Ghidella, 2005) and favored orogenic processes in the N-S trending margin of Chile, which took place dominantly since the Miocene associated with high convergence rates (Ramos, 1999). A modern analog where the effects of oblique versus orthogonal subduction can be observed is the Java-Sumatra region in Southeast Asia (Figure 5c). The convergence vector between the Australian plate and Sunda plate trends NNE. In Sumatra, where the margin trends NNW, subduction is oblique and a strike-slip setting is developed; in contrast, in Java the margin trends WNW and orthogonal subduction produces contractional deformation (Clements et al., 2009; McCaffrey, 2009).

The development of flat-slab subduction has also been proposed as one of the main mechanisms producing upper plate contraction in the Andes (Pilger, 1981; Ramos & Folguera, 2009). In these models, deformation advances toward the foreland with time, associated with the expansion of magmatic activity to the foreland (Ramos & Folguera, 2009). Increased coupling in the subduction zone due to the low angle of the slab has been suggested as a mechanism to increase the main compressional stress (σ_1) orthogonal to the subduction system and hence contractional deformation (Ramos, 2010). Migration of magmatic activity to the foreland linked to shallow subduction has also been proposed as a mechanism for crustal weakening (James & Sacks, 1999; Kay & Mpodozis, 2001; Ramos & Folguera, 2009).

The model of Lamb and Davis (2003) relates interplate coupling to sediment supply to the trench and ultimately climate. Arid climates would reduce sediment supply and increase plate coupling, producing upper plate contraction. This correlates well with the Cenozoic development of the Andes, where the highest segments coincide with areas of arid climate in the Andean region and sediment-starved trenches.

The role of the age of the subducted oceanic lithosphere is not clear, because various models have been proposed. According to Yáñez and Cembrano (2004), the subduction of old lithosphere favors high interplate coupling producing upper plate contraction, and young and warm oceanic lithosphere, in contrast, increases the viscosity of the subduction channel and results in lower coupling and a decrease in upper plate contraction. A different model has been proposed by Protti et al. (1994), who suggest that in the subduction of relatively low-density young oceanic lithosphere, the slab pull forces are canceled by the buoyancy of the slab which opposes subduction. This would impede or slow down the subduction and cause upper plate contraction.

Finally, increases and decreases in magmatic activity have been proposed to be directly correlated to upper plate contraction in some Andean segments (James & Sacks, 1999; Kay & Mpodozis, 2001; Ramos & Folguera, 2009), suggesting that thermal weakening of the crust (Kusznir & Park, 1982) can be an important factor in orogenic development. Most models relate variations in magmatic activity to episodes of flat subduction (James & Sacks, 1999; Kay & Mpodozis, 2001; Ramos & Folguera, 2009) or convergence rate variations (Molnar et al., 1979; Shimozuru & Kubo, 1983).

Overall, it seems that there is no single process that can account for orogenic development in subduction systems. Upper plate absolute velocity and convergence direction and rate are the mechanisms most usually invoked to explain upper plate contractional deformation (Heuret & Lallemand, 2005; Oncken et al., 2006; Ramos, 1999, 2010).

5.2. Exploring the Possible Controls for Miocene Deformation in Costa Rica: Thermal Weakening

Before attempting a comparison between the magmatic and deformation records in Costa Rica, it should be noted that the magmatic record is likely biased, with better information of young episodes due to sampling of fresh rocks suitable for geochronological techniques, and that recent volcanic rocks cover older rocks and poor exposures due to vegetation. Despite this, in most regions of Costa Rica there is a record of magmatic activity much older than the middle to late Miocene (Figure 4). Most Oligocene to middle Miocene magmatic rocks in Costa Rica show calc-alkaline arc affinities (Gazel et al., 2009).

In southern Costa Rica, there is evidence of arc-related volcanic and plutonic rocks as old as 22 Ma in the Cordillera de Talamanca (Alvarado & Gans, 2012). Cessation of "normal" arc magmatism in this region took place between 8 and 5 Ma (de Boer et al., 1995), after which minor volcanism with adakitic affinities is the only igneous activity until magmatic shutdown at 3.5 Ma (Gazel et al., 2011).

In central Costa Rica, island arc magmatism is recorded since 20 Ma, interbedded with sedimentary rocks. Magmatic activity continued in the Miocene with the Aguacate Group, with $^{40}Ar/^{39}Ar$ ages of around 11 Ma (La Cruz Formation). A magmatic gap seems to have taken place between 11 and 7 Ma, associated with the phase of contractional deformation, after which the axis of the magmatic arc in central Costa Rica records a counterclockwise 20–30° rotation (Alvarado & Gans, 2012). The eruption of the Grifo Alto Formation lavas took place between 7 and 3.3 Ma, with geochemical affinities of mature calc-alkaline arc (Alvarado & Gans, 2012). Since the late Pliocene, volcanism was established in the location of the currently active magmatic arc (Alvarado & Gans, 2012).

In the northern region of Costa Rica, the oldest record of arc-related rocks is found in the Sarapiquí arc, northeast of the San Carlos basin. Andesites and rhyolites as old as 28 Ma ($^{40}Ar/^{39}Ar$ age, Gazel et al., 2009) have been found, while most $^{40}Ar/^{39}Ar$ ages of these rocks range between 23 and 11 Ma (Alvarado & Gans, 2012). Southeast of the San Carlos basin, outcrops correspond to ignimbrite sheets of the Bagaces Formation (8–1.6 Ma, Gillot et al., 1994), so no record of middle Miocene and older magmatism is present. The counterclockwise 20–30° rotation of the arc axis is also suggested by the pattern of outcrops, although the volcanic cover of the current arc prevents establishing whether the arc migrated from northeast to southwest or focused in a narrower region.

Therefore, at the regional scale, a magmatic arc was established in Costa Rica since the late Oligocene. During the Miocene, different regions show variations in the location and characteristics of magmatic activity. The northern region of the country shows a continuous record of volcanism, with a migration or retraction from the northeast to the southwest at about 8 Ma. The southern region shows arc-related activity until 8–5 Ma and a complete shutdown of volcanism since 3.5 Ma (Morell, 2015). However, there seems to be no correlation between these variations in magmatic activity and contractional deformation, with the exception of Pliocene uplift of the Cordillera de Talamanca and Fila Costeña and the absence of volcanism. In particular, the onset of deformation in the middle Miocene is not related to any significant event in the magmatic arc (Figure 4). This suggests that plate geodynamics controlled upper plate deformation.

5.3. Exploring the Possible Controls for Miocene Deformation in Costa Rica: Plate Geodynamics

Some of the mechanisms proposed in the Andes can be ruled out for the case of Costa Rica. The role of high absolute trenchward velocity of the upper plate can be ruled out because the Caribbean plate does not present high absolute velocities for the Cenozoic. Some authors even suggest that it has been nearly stationary in the hot spot reference frame since the late Cretaceous (Pindell & Kennan, 2009). The role of increased shear strength in the subduction channel, produced by low sediment supply in an arid climate according to the model of Lamb and Davis (2003), is not supported by the limited studies of climate during the Miocene (Graham, 1987). The development of flat-slab subduction is also not a likely mechanism. The first reason is that it would induce contraction in a more local scale than that which is observed (Figures 4 and 5), and the pattern of migration of deformation toward the foreland, typical of flat-slab subduction, is not observed in Costa Rica. Furthermore, magmatic activity did not expand during contraction but rather focused on the current magmatic arc (Alvarado & Gans, 2012).

We are left with two probable causes for upper plate contraction: (i) the subduction of very young oceanic lithosphere or (ii) the inception of orthogonal convergence between the Cocos and Caribbean plate.

The first process requires that oceanic lithosphere created at the CNS-1 or CNS-2 spreading centers reached the Middle America Trench by 15 Ma, when contractional deformation began. The onset of subduction of CNS created lithosphere has been interpreted from the geochemistry of igneous rocks along the magmatic arc. At present, the limit between crust derived from the East Pacific Rise and from CNS spreading centers is given by the rough-smooth boundary. The rugged topography of the CNS-derived crust is interpreted as a result of its passage over the Galápagos hot spot (Lonsdale & Klitgord, 1978; Morell, 2015; von Huene et al., 1995). The input of an oceanic island basalt component in Costa Rican arc rocks, associated with subduction of the Galápagos hot spot tracks on the Cocos plate, has been recognized since ~8 Ma (de Boer et al., 1995; Gazel et al., 2009). This suggests that this process is not responsible for middle to late Miocene contraction.

In order to evaluate the second mechanism, it is necessary to establish the orientation of the western margin of the Caribbean plate and the direction of movement of the Cocos plate through time.

The orientation of the Pacific margin of Central America has been established since the Oligocene (Montes et al., 2012). The margin presents a roughly WNW to NNW trend from Guatemala to Costa Rica and changes to a main E-W trend in Panama associated with the collision between Central America and South America which produced an oroclinal bend of the Panama Isthmus (Figure 5) (Farris et al., 2011; Montes et al., 2012).

Since the breakup of the oceanic Farallon plate at ~25 Ma, the evolution of the Nazca and Cocos plates in Central America is well constrained by studies of the ocean floor (Barckhausen et al., 2008; Lonsdale, 2005; Meschede & Barckhausen, 2000; Meschede et al., 1998; Pindell & Kennan, 2009). Three different spreading centers opened consecutively between the Nazca and Cocos plates, denominated CNS-1, CNS-2, and the currently active CNS-3 (Figure 1) (Barckhausen et al., 2001). Prior to the breakup, the movement of the Farallon plate responded to spreading in the East Pacific Rise and slab pull along the dominantly N-S Pacific margin of the Americas. It followed a roughly E-W or ENE strike (Figure 5d), oblique to the southern Central America margin (Barckhausen et al., 2008). The present movement of the Cocos plate is toward the NNE, orthogonal to the Middle America Trench. Based on the reconstruction of the development of CNS centers (Barckhausen et al., 2008; Meschede & Barckhausen, 2000; Meschede et al., 1998), we propose that the change from oblique to orthogonal convergence as a result of Farallon plate breakup was gradual during the middle Miocene. Convergence between the Cocos and Nazca plates during the activity of CNS-1 (25–19.5 Ma, Meschede et al., 1998) was still controlled by spreading on the East Pacific Rise (Barckhausen et al., 2008), probably due to the high velocity of spreading along this center (Wilson, 1996). During this time, the high obliquity of subuction probably led to the development of a strike-slip system subparallel to the margin (Figure 5). According to Barckhausen et al. (2008), the Cocos and Nazca plates were able to move as separate plates since ~19 Ma, as documented in magnetic anomalies younger than chron 6 (18.8 Ma according to the timescale of Cande & Kent, 1995). The opening of CNS-2 (19.5–14.7 Ma, Meschede et al., 1998) and CNS-3 after 14.7 Ma, each with a more E-W trend, could have produced the change to a NNE movement of the Cocos plate, producing orthogonal subduction along the Middle America trench (Figure 5e) (see also Meschede et al., 1998, their Figure 5). By at least 14.5 Ma, NNE movement of the Cocos plate was well established, as shown by the orientation of the Cocos Ridge. At the NE end of the ridge, basalts have provided $^{40}Ar/^{39}Ar$ ages of 13 to 14.5 Ma (Werner et al., 1999), indicating that since that moment, the Cocos plate moved over the Galápagos hot spot with NNE trend. The most recent reconstructions of the evolution of the Cocos and Nazca plates indicate that the Sandra Rift (Figure 1) was active as part of the CNS-3 since ~14 Ma (Lonsdale, 2005). The easternmost sector of the Cocos plate was captured by the Nazca plate at 8 Ma through propagation of the Panama-Coiba fracture zones according to Morell (2015). The Sandra Rift ceased spreading at this time. Therefore, orthogonal convergence between the Cocos plate and the Middle America trench took place along the Costa Rican sector of the trench between ~18 and 8 Ma. The development of the Panama/Coiba fracture zones between 8 Ma and the present produced the current situation where the Cocos plate subducts beneath Costa Rica, and Nazca plate subduction is limited to Panama (Figure 2).

If our proposal is correct, we expect that the middle to late Miocene deformation phase is also recorded in the rest of Central America where the trench was perpendicular to the convergence direction. The subduction zone in Nicaragua is at present one of the best examples of a convergent margin with arc and back-arc extensional tectonics (e.g., Burkart and Self, 1985; Ramos, 2010). Some researchers suggest that this regime is active since the Oligocene, as recorded in the migration of magmatism toward the trench. However, other works indicate that this migration took place after ~11 Ma, with the middle Miocene corresponding to the maximum migration toward the foreland of the arc (Alvarado & Gans, 2012; Saginor et al., 2013). In addition to this, Weinberg (1992) and Kumpulainen (1995) report a late Miocene event of contractional deformation in Nicaragua. Ranero et al. (2000) indicate accelerated tectonism and basin inversion in early and middle Miocene times in Nicaragua, which they relate to a plate reorganization involving the collision of Central America and South America. These contractional events could be related to orthogonal subduction of the Cocos plate. In this case, the current extensional configuration of the Nicaragua subduction zone would be produced in the latest Miocene, after the contractional event.

As documented in many previous works and summarized here, the middle to late Miocene episode of contractional deformation is conspicuously recorded in Costa Rica and perhaps extended to Nicaragua (Figures 4 and 5), implying a trigger at the regional to plate scale. The oldest record of contractional deformation determined until now is in the Fila Costeña at about 15 Ma. We propose that the inception of orthogonal convergence between the Cocos and Caribbean plates between 19 and 14 Ma was the trigger for this widespread contractional deformation. Furthermore, the onset and intensity of contraction in the different regions was likely controlled by factors related to the physical properties of the upper plate, such as the rheological state determined by composition and thermal regime, the presence and orientation of preexisting faults, and subtle variations in the orientation of the margin and the convergence velocity along the Middle America trench. It is hard to evaluate these processes in detail with the available constraints on deformation timing. More work is needed to refine the chronology of deformation and the structural styles, in order to obtain a more complete understanding of the Miocene evolution of Central America. The end of this contractional event took place between 8 and 5 Ma, probably associated with the major change in the geodynamic setting produced by the development of the Coiba/Panama fracture zones and the capture of the eastern part of the Cocos plate by the Nazca plate. The arrival at the trench of the Cocos Ridge at 3–2 Ma further modified the geodynamic setting, leading to the present configuration in which contraction is predominant only in southern Costa Rica, and the Central Costa Rica Deformed Belt shows mostly strike-slip kinematics (e.g., Marshall et al., 2000). In Nicaragua, the migration of the magmatic arc toward the trench and the establishment of an extensional regime is associated with a steepening of the slab (Ramos, 2010) in the late Miocene (Alvarado & Gans, 2012; Saginor et al., 2013).

6. Conclusions

The review of evidence for a middle to late Miocene contractional deformation event in Costa Rica reveals that this event was recorded in most regions of the country. Basin inversion is recorded in the Fila Costeña and Cordillera de Talamanca since 15 Ma. In all regions, the period between 11 and 8 Ma shows widespread contractional deformation. The predominant trend of the structures developed during this event is NW to WNW, roughly parallel to the Middle America Trench. The large area affected indicates a mechanism operating at the plate scale, underscoring the importance of this event, which in turn has great implications for the tectonic evolution of Central America. We suggest that contraction was triggered by a change from oblique to orthogonal subduction of the Cocos plate below the Caribbean plate starting at 19 Ma. This change was associated with the onset of spreading in Cocos-Nazca spreading centers with orientation gradually approaching E-W: CNS-2 at 19.5 Ma and CNS-3 at 14.7 Ma. In this way, middle to late Miocene contraction in Central America would respond to a process observed in other subduction zones like the Andes. We conclude that convergence direction is an important factor in subduction zones, where it can control the stress state of the upper plate resulting in the development of strike-slip margins or contractional deformation.

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References

Abratis, M., & Wörner, G. (2001). Ridge collision, slab-window formation, and the flux of Pacific asthenosphere into the Caribbean realm. *Geology*, *29*(2), 127–130. https://doi.org/10.1130/0091-7613(2001)029%3C0127:RCSWFA%3E2.0.CO;2

Alvarado, G. E., Dengo, C., Martens, U., Bundschuh, J., Aguilar, T., & Bonis, S. B. (2007). Stratigraphy and geologic history. In J. Bundschuh & G. E. Alvarado (Eds.), *Central America: Geology, resources and hazards* (pp. 345–394). London: Taylor & Francis.

Alvarado, G. E., & Gans, P. B. (2012). Síntesis geocronológica del magmatismo, metamorfismo y metalogenia de Costa Rica, América Central. *Revista Geologica de America Central*, *46*, 7–122.

Aragón, E., D'eramo, F., Castro, A., Pinotti, L., Brunelli, D., Rabbia, O., … Ribot, A. (2011). Tectono-magmatic response to major convergence changes in the north Patagonian suprasubduction system; the Paleogene subduction–transcurrent plate margin transition. *Tectonophysics*, *509*(3-4), 218–237. https://doi.org/10.1016/j.tecto.2011.06.012

Astorga, A., Fernández, J. A., Barboza, G., Campos, L., Obando, J., Aguilar, A., & Obando, L. G. (1991). Cuencas sedimentarias de Costa Rica: Evolución geodinámica y potencial de hidrocarburos. *Revista Geologica de America Central*, *13*, 25–59.

Ballestero, L. E., Dobrinescu, M. M., Jager, G., & Mayers, I. R. (1995). An integrated geological and geophysical interpretation of the San Carlos basin, Costa Rica. In R. L. Miller, G. Escalante, J. A. Reinemund, & M. J. Bergin (Eds.), *Energy and mineral potential of the Central American–Caribbean regions, Earth Sciences Series 16* (pp. 95–103). Houston: Circum-Pacific Council for Energy and Mineral Resources. https://doi.org/10.1007/978-3-642-79476-6_11

Barboza, G., Barrientos, J., & Astorga, A. (1995). Tectonic evolution and sequence stratigraphy of the Central Pacific margin of Costa Rica. *Revista Geologica de America Central*, *18*, 43–63.

Barckhausen, U., Ranero, C. R., Cande, S. C., Engels, M., & Weinrebe, W. (2008). Birth of an intraoceanic spreading center. *Geology*, *36*, 767–770. https://doi.org/10.1130/G25056A.1

Barckhausen, U., Ranero, C. R., von Huene, R., Cande, S. C., & Roeser, H. A. (2001). Revised tectonic boundaries in the Cocos Plate off Costa Rica: Implications for the segmentation of the convergent margin and for plate tectonic models. *Journal of Geophysical Research*, *106*(B9), 19,207–19,220. https://doi.org/10.1029/2001JB000238

Baumgartner, P. O., Mora, C., Butterlin, J., Sigal, J., Glacon, G., Azema, J., & Bourgois, J. (1984). Sedimentación y paleogeografía del Cretácico y Cenozoico del litoral Pacífico de Costa Rica. *Revista Geologica de America Central*, *1*, 57–136.

Bellon, H., & Tournon, J. (1978). Contribution de la géochronométrie K-Ar a l'etude du magmatisme de Costa Rica, Amérique Central. *Bulletin de la Societe Geologique de France*, *20*(6), 955–959.

Brandes, C., Astorga, A., Back, S., Littke, R., & Winsemann, J. (2007). Deformation style and basin-fill architecture of the offshore Limón back arc basin (Costa Rica). *Marine and Petroleum Geology*, *24*, 277–287. https://doi.org/10.1016/j.marpetgeo.2007.03.002

Brandes, C., Astorga, A., Littke, R., & Winsemann, J. (2008). Basin modelling of the Limón Back-arc Basin (Costa Rica): Burial history and temperature evolution of an island arc-related basin-system. *Basin Research*, *20*(1), 119–142. https://doi.org/10.1111/j.1365-2117.2007.00345.x

Burkart, B., & Self, S. (1985). Extension and rotation of crustal blocks in northern Central America and effect on the volcanic arc. *Geology*, *13*(1), 22–26. https://doi.org/10.1130/0091-7613(1985)13%3C22:EAROCB%3E2.0.CO;2

Cande, S. C., & Kent, D. V. (1995). Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic. *Journal of Geophysical Research*, *100*(B4), 6093–6095. https://doi.org/10.1029/94JB03098

Clements, B., Hall, R., Smyth, H. R., & Cottam, M. (2009). Thrusting of a volcanic arc: A new structural model for Java. *Petroleum Geoscience*, *15*, 159–174. https://doi.org/10.1144/1354-079309-831

Cloos, M. (1993). Lithospheric buoyancy and collisional orogenesis: Subduction of oceanic plateaus, continental margins, island arcs, spreading ridges and seamounts. *Geological Society of America Bulletin*, *105*(6), 715–737. https://doi.org/10.1130/0016-7606(1993)105%3C0715:LBACOS%3E2.3.CO;2

de Boer, J. Z., Drummond, M. S., Bordelon, M. J., Defant, M. J., Bellon, H., & Maury, R. C. (1995). Cenozoic magmatic phases of the Costa Rican island arc (Cordillera de Talamanca). In P. Mann (Ed.), *Geologic and tectonic development of the Caribbean Plate Boundary in southern Central America, Geological Society of America Special Paper* (Vol. 295, pp. 35–55). Boulder, CO: Geological Society of America. https://doi.org/10.1130/SPE295-p35

Dengo, G. (1962). Tectonic-igneous sequence in Costa Rica. In A. E. J. Engel, H. L. James, & B. F. Leonard (Eds.), *Petrologic studies; a volume in honor of A.F. Budington* (pp. 133–161). Boulder, CO: Geological Society of America.

Denyer, P., Aguilar, T., & Montero, W. (2014). *Cartografía geológica de la península de Nicoya*. San José: Editorial de la Universidad de Costa Rica.

Denyer, P., & Alvarado, G. E. (2007). Mapa geológico de Costa Rica (escala 1:500,000), Map printed in San Jose, Costa Rica by Dirección de Geología y Minas (MINAE).

Denyer, P., Alvarado, G. E., & Aguilar, T. (2000). Historia geológica. In P. Denyer & S. Kussmaul (Eds.), *Geología de Costa Rica* (pp. 155–167). Cartago: Editorial Tecnológica de Costa Rica.

Denyer, P., & Arias, O. (1991). Estratigrafía de la región central de Costa Rica. *Revista Geologica de America Central*, *12*, 1–59.

Denyer, P., & Kussmaul, S. (2000). Introducción: Aspectos generales y filosóficos. In P. Denyer & S. Kussmaul (Eds.), *Geología de Costa Rica* (pp. 9–13). Cartago: Editorial Tecnológica de Costa Rica.

Dewey, J. F., & Bird, J. M. (1970). Mountain belts and the new global tectonics. *Journal of Geophysical Research*, *75*(14), 2625–2647. https://doi.org/10.1029/JB075i014p02625

Dzierma, Y., Rabbel, W., Thorwart, M. M., Flueh, E. R., Mora, M. M., & Alvarado, G. E. (2011). The steeply subducting edge of the Cocos Ridge: Evidence from receiver functions beneath the northern Talamanca Range, south-central Costa Rica. *Geochemistry, Geophysics, Geosystems*, *12*, Q04S30. https://doi.org/10.1029/2010GC003477

Dzierma, Y., Thorwart, M. M., Rabbel, W., Flueh, E. R., Alvarado, G. E., & Mora, M. M. (2010). Imaging crustal structure in south central Costa Rica with receiver functions. *Geochemistry, Geophysics, Geosystems*, *11*, Q08S26. https://doi.org/10.1029/2009GC002936

Farris, D. W., Jaramillo, C., Bayona, G., Restrepo-Moreno, S., Montes, C., Cardona, A., … Valencia, V. (2011). Fracturing of the Panamanian Isthmus during initial collision with South America. *Geology*, *39*(11), 1007–1010. https://doi.org/10.1130/G32237.1

Fisher, D. M., Gardner, T. W., Sak, P., Sanchez, J. D., Murphy, K., & Vannucchi, P. (2004). Active thrusting in the inner forearc of an erosive convergent margin, Pacific coast, Costa Rica. *Tectonics*, *23*, TC2007. https://doi.org/10.1029/2002TC001464

Forsyth, D. W., & Uyeda, S. (1975). On the relative importance of the driving forces of plate motion. *Geophysical Journal of the Royal Astronomical Society*, *43*(1), 163–200. https://doi.org/10.1111/j.1365-246X.1975.tb00631.x

Gardner, T. W., Verdonck, D., Pinter, N. M., Slingerland, R., Furlong, K. P., Bullard, T. F., & Wells, S. G. (1992). Quaternary uplift astride the aseismic Cocos Ridge, Pacific coast, Costa Rica. *Geological Society of America Bulletin*, *104*(2), 219–232. https://doi.org/10.1130/0016-7606(1992)104%3C0219:QUATAC%3E2.3.CO;2

Gazel, E., Alvarado, G. E., Obando, J., & Alfaro, A. (2005). Evolución magmática del arco de Sarapiquí, Costa Rica. *Revista Geologica de America Central*, *32*, 13–31.

Gazel, E., Carr, M. J., Hoernle, K., Feigenson, M. D., Szymanski, D., Hauff, F., & van den Bogaard, P. (2009). Galapagos-OIB signature in southern Central America: Mantle refertilization by arc-hot spot interaction. *Geochemistry, Geophysics, Geosystems*, *10*, Q02S11. https://doi.org/10.1029/2008GC002246

Gazel, E., Hoernle, K., Carr, M. J., Herzberg, C., Saginor, I., van den Bogaard, P., … Swisher, C. III (2011). Plume–subduction interaction in southern Central America: Mantle upwelling and slab melting. *Lithos*, *121*, 117–134. https://doi.org/10.1016/j.lithos.2010.10.008

Gillot, P. Y., Chiesa, S., & Alvarado, G. E. (1994). Chronostratigraphy of upper Miocene-Quaternary volcanism in northern Costa Rica. *Revista Geologica de America Central*, *17*, 45–53.

Graham, A. (1987). Miocene communities and paleoenvironments of southern Costa Rica. *American Journal of Botany*, *74*(10), 1501–1518. https://doi.org/10.2307/2444045

Gursky, M. M. (1988). Análisis tectónico de la península de Nicoya (Costa Rica) y su significado para el desarrollo estructural—Geodinámico de América Central meridional. *Revista Geologica de America Central*, *8*, 19–75.

Heuret, A., & Lallemand, S. (2005). Plate motions, slab dynamics and back-arc deformation. *Physics of the Earth and Planetary Interiors*, *149*, 31–51. https://doi.org/10.1016/j.pepi.2004.08.022

Hey, R. (1977). Tectonic evolution of the Cocos-Nazca spreading. *Geological Society of America Bulletin*, *88*(10), 1404–1420. https://doi.org/10.1130/0016-7606(1977)88%3C1404:TEOTCS%3E2.0.CO;2

James, D. E., & Sacks, S. (1999). Cenozoic formation of the Central Andes: A geophysical perspective. In B. Skinner (Ed.), *Geology and mineral deposits of Central Andes, Society of Economic Geologists Special Publication* (Vol. 7, pp. 1–25). Boulder, CO: Society of Economic Geology.

Kay, S. M., & Mpodozis, C. (2001). Central Andean ore deposits linked to evolving shallow subduction systems and thickening crust. *GSA Today*, *11*(3), 4–9. https://doi.org/10.1130/1052-5173(2001)011%3C0004:CAODLT%3E2.0.CO;2

Kesel, R. H. (1983). Quaternary history of the Río General Valley, Costa Rica. *National Geographic Society Research Reports*, *15*, 339–358.

Kolarsky, R. A., Mann, P., & Montero, P. W. (1995). Island arc response to shallow subduction of the Cocos Ridge, Costa Rica. In P. Mann (Ed.), *Geologic and tectonic development of the Caribbean Plate Boundary in southern Central America*, *Geological Society of America Special Paper* (Vol. 295, pp. 235–262). Boulder, CO: Geological Society of America. https://doi.org/10.1130/SPE295-p235

Kumpulainen, R. A. (1995). Stratigraphy and sedimentology in western Nicaragua. *Revista Geologica de America Central*, *18*, 91–95.

Kussmaul, S. (2000). Estratigrafía de las rocas ígneas. In P. Denyer & S. Kussmaul (Eds.), *Geología de Costa Rica* (pp. 63–86). Cartago: Editorial Tecnológica de Costa Rica.

Kusznir, N. J., & Park, R. G. (1982). Intraplate lithosphere strength and heat flow. *Nature*, *299*(5883), 540–542. https://doi.org/10.1038/299540a0

Lamb, S., & Davis, P. (2003). Cenozoic climate change as a possible cause for the rise of the Andes. *Nature*, *425*(6960), 792–797. https://doi.org/10.1038/nature02049

Linkimer, L., & Aguilar, T. (2000). Estratigrafía sedimentaria. In P. Denyer & S. Kussmaul (Eds.), *Geología de Costa Rica* (pp. 43–62). Cartago: Editorial Tecnológica de Costa Rica.

Lonsdale, P. (2005). Creation of the Cocos and Nazca plates by fission of the Farallon plate. *Tectonophysics*, *404*, 237–264. https://doi.org/10.1016/j.tecto.2005.05.011

Lonsdale, P., & Klitgord, K. D. (1978). Structure and tectonic history of the eastern Panama Basin. *Geological Society of America Bulletin*, *89*(7), 981–999. https://doi.org/10.1130/0016-7606(1978)89%3C981:SATHOT%3E2.0.CO;2

Lücke, O. H., & Arroyo, I. G. (2015). Density structure and geometry of the Costa Rican subduction zone from 3-D gravity modeling and local earthquake data. *Solid Earth*, *6*(1), 1–8. https://doi.org/10.5194/se-6-1-2015

MacMillan, I., Gans, P. B., & Alvarado, G. (2004). Middle Miocene to present plate tectonic history of the southern Central American volcanic arc. *Tectonophysics*, *392*, 325–348. https://doi.org/10.1016/j.tecto.2004.04.014

Marshall, J. S., Fisher, D. M., & Gardner, T. W. (2000). Central Costa Rica deformed belt: Kinematics of diffuse faulting across the western Panama block. *Tectonics*, *19*(3), 468–492. https://doi.org/10.1029/1999TC001136

Marshall, J. S., & Idleman, B. D. (1999). $^{40}Ar/^{39}Ar$ age constraints on Quaternary landscape evolution of the central volcanic arc and Orotina debris fan, Costa Rica. Paper presented at the Geological Society of America Annual Meeting, Geological Society of America, Denver.

Marshall, J. S., Idleman, B. D., Gardner, T. W., & Fisher, D. M. (2003). Landscape evolution within a retreating volcanic arc, Costa Rica, Central America. *Geology*, *31*(5), 419–422. https://doi.org/10.1130/0091-7613(2003)031%3C0419:LEWARV%3E2.0.CO;2

McCaffrey, R. (2009). The tectonic framework of the Sumatran subduction zone. *Annual Review of Earth and Planetary Sciences*, *37*, 345–366. https://doi.org/10.1146/annurev.earth.031208.100212

Meschede, M., & Barckhausen, U. (2000). Plate tectonic evolution of the Cocos-Nazca spreading center. In E. A. Silver, G. Kimura, & T. H. Shipley (Eds.), *Fluids, mass and thermal fluxes in the Pacific margin of Costa Rica, Proceedings of the Ocean Drilling Program, Scientific Results, Volume 170* (Chap. 7, 10 pp.). Ms170SR-009. College Station, TX: Ocean Drilling Project Publications. https://doi.org/10.2973/odp.proc.sr.170.009.2000

Meschede, M., Barckhausen, U., & Worm, H. U. (1998). Extinct spreading ridges on the Cocos plate. *Terra Nova*, *10*(4), 211–216. https://doi.org/10.1046/j.1365-3121.1998.00195.x

Meschede, M., Zweigel, P., Frisch, W., & Völker, D. (1999). Mélange formation by subduction erosion: The case of the Osa mélange in southern Costa Rica. *Terra Nova*, *11*(4), 141–148. https://doi.org/10.1046/j.1365-3121.1999.00237.x

Molnar, P., Freedman, D., & Shih, J. S. (1979). Lengths of intermediate and deep seismic zones and temperatures in downgoing slabs of lithosphere. *Geophysical Journal of the Royal Astronomical Society*, *56*(1), 41–54. https://doi.org/10.1111/j.1365-246X.1979.tb04766.x

Montero, W. P. (2000). Geotectónica. In P. Denyer & S. Kussmaul (Eds.), *Geología de Costa Rica* (pp. 115–132). Cartago: Editorial Tecnológica de Costa Rica.

Montes, C., Bayona, G., Cardona, A., Buchs, D. M., Silva, C. A., Morón, S., … Valencia, V. (2012). Arc-continent collision and orocline formation: Closing of the Central American seaway. *Journal of Geophysical Research*, *117*, B04105. https://doi.org/10.1029/2011JB008959

Morell, K. D. (2015). Late Miocene to recent plate tectonic history of the southern Central America convergent margin. *Geochemistry, Geophysics, Geosystems*, *16*(10), 3362–3382. https://doi.org/10.1002/2015GC005971

Morell, K. D. (2016). Seamount, ridge and transform subduction in southern Central America. *Tectonics*, *35*(2), 357–385. https://doi.org/10.1002/2015TC003950

Morell, K. D., Kirby, E., Fisher, D. M., & van Soest, M. (2012). Geomorphic and exhumational response of the Central American volcanic arc to Cocos Ridge subduction. *Journal of Geophysical Research*, *117*, B04409. https://doi.org/10.1029/2011JB008969

Mpodozis, C., & Ramos, V. A. (1989). The Andes of Chile and Argentina. In G. E. Ericksen, M. T. Cañas Pinochet, & J. A. Reinemund (Eds.), *Geology of the Andes and its relation to energy and mineral resources, Earth Sciences Series 14* (pp. 59–90). Houston, TX: Circum-Pacific Council for Energy and Mineral Resources.

Müller, R. D., Seton, M., Zahirovic, S., Williams, S. E., Matthews, K. J., Wright, N., … Cannon, J. (2016). Ocean basin evolution and global-scale plate reorganization events since Pangea break-up. *Annual Review of Earth and Planetary Sciences*, *44*(1), 107–138. https://doi.org/10.1146/annurev-earth-060115-012211

Oncken, O., Chong, G., Franz, G., Giese, P., Götze, H.-J., Ramos, V. A., … Wigger, P. (Eds) (2006). *The Andes—Active subduction orogeny*. Berlin: Springer Frontiers in Earth Sciences Series.

Pardo-Casas, F., & Molnar, P. (1987). Relative motion of the Nazca (Farallon) and South American Plates since Late Cretaceous time. *Tectonics*, *6*(3), 233–248. https://doi.org/10.1029/TC006i003p00233

Pilger, R. H. (1981). Plate reconstructions, aseismic ridges, and low-angle subduction beneath the Andes. *Geological Society of America Journal*, *92*(7), 448–456. https://doi.org/10.1130/0016-7606(1981)92%3C448:PRARAL%3E2.0.CO;2

Pindell, J., & Kennan, L. (2009). Tectonic evolution of the Gulf of Mexico, Caribbean and northern South America in the mantle reference frame: An update. In K. H. James, M. A. Lorente, & J. Pindell (Eds.), *The origin and evolution of the Caribbean Plate*, *Geological Society of London Special Publication* (Vol. 328, pp. 1–55). London: Geological Society.

Protti, M., Güendel, F., & McNally, K. (1994). The geometry of the Wadati-Benioff zone under southern Central America and its tectonic significance: Results from a high-resolution local seismographic network. *Physics of the Earth and Planetary Interiors*, *84*(1-4), 271–287. https://doi.org/10.1016/0031-9201(94)90046-9

Protti, M., Güendel, F., & McNally, K. (1995). Correlation between the age of the subducting Cocos Plate and the geometry of the Wadati-Benioff zone under Nicaragua and Costa Rica. In P. Mann (Ed.), *Geologic and tectonic development of the Caribbean Plate Boundary in southern Central America*, *Geological Society of America Special Paper* (Vol. 295, pp. 309–326). Boulder, CO: Geological Society of America. https://doi.org/10.1130/SPE295-p309

Ramos, V. A. (1999). Plate tectonic setting of the Andean cordillera. *Episodes*, *22*(3), 183–190.

Ramos, V. A. (2010). The tectonic regime along the Andes: Present-day and Mesozoic regimes. *Geological Journal*, *45*(1), 2–25. https://doi.org/10.1002/gj.1193

Ramos, V. A., & Folguera, A. (2009). Andean flat-subduction through time. In J. B. Murphy, J. D. Keppie, & A. J. Hynes (Eds.), *Ancient orogens and modern analogues*, *Geological Society of London Special Publication* (Vol. 327, pp. 31–54). London: Geological Society.

Ranero, C. R., vonHuene, R., Flueh, E., Duarte, M., Baca, D., & McIntosh, K. (2000). A cross-section of the convergent Pacific margin of Nicaragua. *Tectonics*, *19*(2), 335–357. https://doi.org/10.1029/1999TC900045

Saginor, I., Gazel, E., Condie, C., & Carr, M. (2013). Evolution of geochemical variations along the Central American volcanis front. *Geochemistry, Geophysics, Geosystems*, *14*(10), 4504–4522. https://doi.org/10.1002/ggge.20259

Seyfried, H., Astorga, A., Amann, H., Calvo, C., Kolb, W., Schmidt, H., & Winsemann, J. (1991). Anatomy of an evolving island arc: Tectonic and eustatic control in the south Central American fore-arc area. In D. I. M. McDonald (Ed.), *Sedimentation, tectonics and eustasy: Sea-level changes at active margins*, *Sp. Pub. Int. Assoc. Sediment* (Vol. 12, pp. 217–240). Oxford: Blackwell Publishing Ltd. https://doi.org/10.1002/9781444303896.ch13

Shimozuru, D., & Kubo, N. (1983). Volcano spacing and subduction. In D. Shimozuru & I. Yokoyama (Eds.), *Arc volcanism: Physics and tectonics* (pp. 141–151). Tokyo: Terra Publishers.

Sitchler, J. C., Fisher, D. M., Gardner, T. W., & Protti, M. (2007). Constraints on inner forearc deformation from balanced cross sections, Fila Costeña thrust belt, Costa Rica. *Tectonics*, *26*, TC6012. https://doi.org/10.1029/2006TC001949

Somoza, R., & Ghidella, M. E. (2005). Convergencia en el margen occidental de América del Sur durante el Cenozoico: Subducción de las placas de Nazca, Farallón y Aluk. *Revista de la Asociación Geológica Argentina*, *60*, 797–809.

Somoza, R., & Zaffarana, C. B. (2008). Mid-Cretaceous polar standstill of South America, motion of the Atlantic hotspots and the birth of the Andean cordillera. *Earth and Planetary Science Letters*, *271*(1-4), 267–277. https://doi.org/10.1016/j.epsl.2008.04.004

Steinmann, G. (1929). *Geologie von Perú*. Heidelberg: Carl Winters Universitatsbuchhandlung.

Tournon, J., & Alvarado, G. E. (1995). Mapa geológico de Costa Rica Escala 1:500.000. Cooperación Científica Tecnológica de Francia - Instituto Costarricence de Electricidad, París.

von Huene, R., Bialas, J., Flueh, E., Cropp, B., Csernok, T., Fabel, E., … Barrios L., O. (1995). Morphotectonics of the Pacific convergent margin of Costa Rica. In P. Mann (Ed.), *Geologic and tectonic development of the Caribbean Plate Boundary in southern Central America*, *Geological Society of America Special Paper*, (Vol. 295, pp. 291–307). Boulder, CO: Geological Society of America. https://doi.org/10.1130/SPE295-p291

Walther, C. H. E. (2003). The crustal structure of the Cocos Ridge off Costa Rica. *Journal of Geophysical Research*, *108*(B3), 2136. https://doi.org/10.1029/2001JB000888

Weinberg, R. F. (1992). Neotectonic development of western Nicaragua. *Tectonics*, *11*(5), 1010–1017. https://doi.org/10.1029/92TC00859

Werner, R., Hoernle, K., van den Bogaard, P., Ranero, C., von Huene, R., & Korich, D. (1999). Drowned 14-m.y.-old Galápagos archipelago off the coast of Costa Rica: Implications for tectonic and evolutionary models. *Geology*, *27*(6), 499–502. https://doi.org/10.1130/0091-7613(1999)027%3C0499:DMYOGP%3E2.3.CO;2

Weyl, R. (1957). *Contribución a la geología de la Cordillera de Talamanca de Costa Rica*. San José: Instituto Geográfico.

Wilson, D. S. (1996). Fastest known spreading on the Miocene Cocos-Pacific plate boundary. *Geophysical Research Letters*, *23*(21), 3003–3006. https://doi.org/10.1029/96GL02893

Yáñez, G., & Cembrano, J. (2004). Role of viscous plate coupling in the late Tertiary Andean tectonics. *Journal of Geophysical Research*, *109*, B02407. https://doi.org/10.1029/2003JB002494