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Changing tectonic regimes in the central Costa Rica forearc between the Paleogene and the present: Insights from structural analysis and focal mechanisms

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ABSTRACT

We discuss the Cenozoic history of the Central Costa Rica forearc, between 10° and 9°30′N, based on geological mapping, fault slip data and seismological records.The temporal variability in the regional stress-field suggests a variable and complex deformation pattern. The first stage of deformation, from the Paleogene to early Miocene, was controlled by an extensional regime in the forearc. Afterwards, a change to orthogonal convergence triggered a contractional deformation and subsequent inversion of the sedimentary extensional basins in the middle-upper Miocene. Finally, a transpressive regime has been developed since the Pliocene.

1. Introduction

The evolution of the Costa Rica forearc records a complex geologic history related to subduction along the Middle America Trench since the Late Cretaceous. The subduction processes are characterized by oceanic terrane accretion, lithospheric plate reorganizations, subduction of fracture zones, aseismic ridges and seamounts, changes in the subduction angle including slab roll-back and flat slab, variations in orientation and velocity of plate movements which influenced the history of the upper plate (Meschede et al., 1998; Meschede and Barckhausen, 2000; Fisher et al., 2004; MacMillan et al., 2004; Sitchler et al., 2007; Pindell and Kennan, 2009; Morell et al., 2012; Morell, 2016; Mescua et al., 2017).

However, the role of strike-slip, reverse and extensional tectonics in the Neogene-Quaternary evolution of the Central Costa Rica forearc (Fig. 1) has not been widely investigated. The study area is a major part of the Costa Rica forearc, filled by 2000 m of an Oligocene to Holocene sedimentary succession (Denyer and Arias, 1991). This sedimentary succession rests unconformably on Cretaceous-Paleocene oceanic terranes (Arias, 2003). During the Paleocene to Neogene, this succession has been interpreted as the result of passive sedimentation on top of a Cretaceous paleorelief by some authors (e.g., Sitchler et al., 2007; Denyer and Alvarado, 2007; Arias, 2003), whereas others indicate a strong structural control by normal or strike-slip faults (Astorga et al., 1991; Obando et al., 1991; Barboza et al., 1995; Bolz and Calvo, 2003). Afterwards, from middle to late Miocene, different studies found evidence for important contractional deformation in Costa Rica (MacMillan et al., 2004; Mescua et al., 2017); whereas others have recognized a Pliocene contractional event (Gardner et al., 1992; Protti et al., 1995; Abratis and Wörner, 2001). Further, the present-day deformation is complex, with many faults showing strike-slip motion. These faults have been interpreted to produce a forearc sliver with trench-parallel displacement (Lewis et al., 2008; López, 2012), or as the boundary between two major crustal blocks or subplates known as the Panamá block and the Caribbean plate (Kobayashi et al., 2014; Norabuena et al., 2004; Montero, 2000).

Three important tectonic events have been suggested to explain the changes in the structural styles along the forearc (i) arrival of the Cocos Ridge at the Middle America trench in the Pliocene (Gardner et al., 1992; Abratis and Wörner, 2001; Morell, 2016); (ii) subduction of an

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ancient ridge during the Neogene (Brandes and Winsemann, 2018) and; (iii) reorganization of tectonic plates during the middle to late Miocene (e.g., MacMillan et al., 2004; Mescua et al., 2017). These studies have focused in different time periods without reaching a consensus on the events that trigger different styles of deformation.

In this contribution, we integrate previously published data with new seismological and structural data to analyze the style and distribution of deformation in Central Costa Rica forearc (Fig. 1). We reconstruct the tectonostratigraphy from the Neogene to Quaternary in the key region of central Costa Rica forearc, to assess the kinematic response to the plate boundary dynamics through time.

2. Geological background

We divide the Central Costa Rica forearc in outer and inner inland sectors characterized by different lithologies and contrasting tectonic behaviour (Figs. 1 and 2). The outer forearc contains the basement and the undeformed sedimentary Parrita basin while the inner forearc includes the Montes del Aguacate magmatic arc, the deformed Candelaria and Térraba sedimentary basins and the valle central basin. The stratigraphy of the study area can be divided into three main stages (i) Upper Cretaceous basement igneous rocks; (ii) Cenozoic sedimentary successions of the Candelaria and Térraba basins; and (iii) Miocene-Pliocene volcanic arc rocks (Astorga et al., 1991; Denyer and Arias, 1991; Obando et al., 1991; Arias, 2003). Pliocene-Quaternary deposits are also found in some areas (Fig. 2).

2.1. Basement rocks

The basement of the study area corresponds to the Cretaceous Nicoya Complex, considered part of the Caribbean Large Igneous Province (CLIP) (Sinton et al., 1997; Hauff et al., 2000; Arias, 2003) (Figs. 2 and 3), and the Late Cretaceous-Eocene Tulin Formation (Arias, 2003).

The Nicoya Complex is composed of pillow and massive tholeiitic basalts, volcanic breccias, dolerites, gabbros, scarce plagiogranites and hyaloclastites (Hauff et al., 2000). Its age has been constrained by

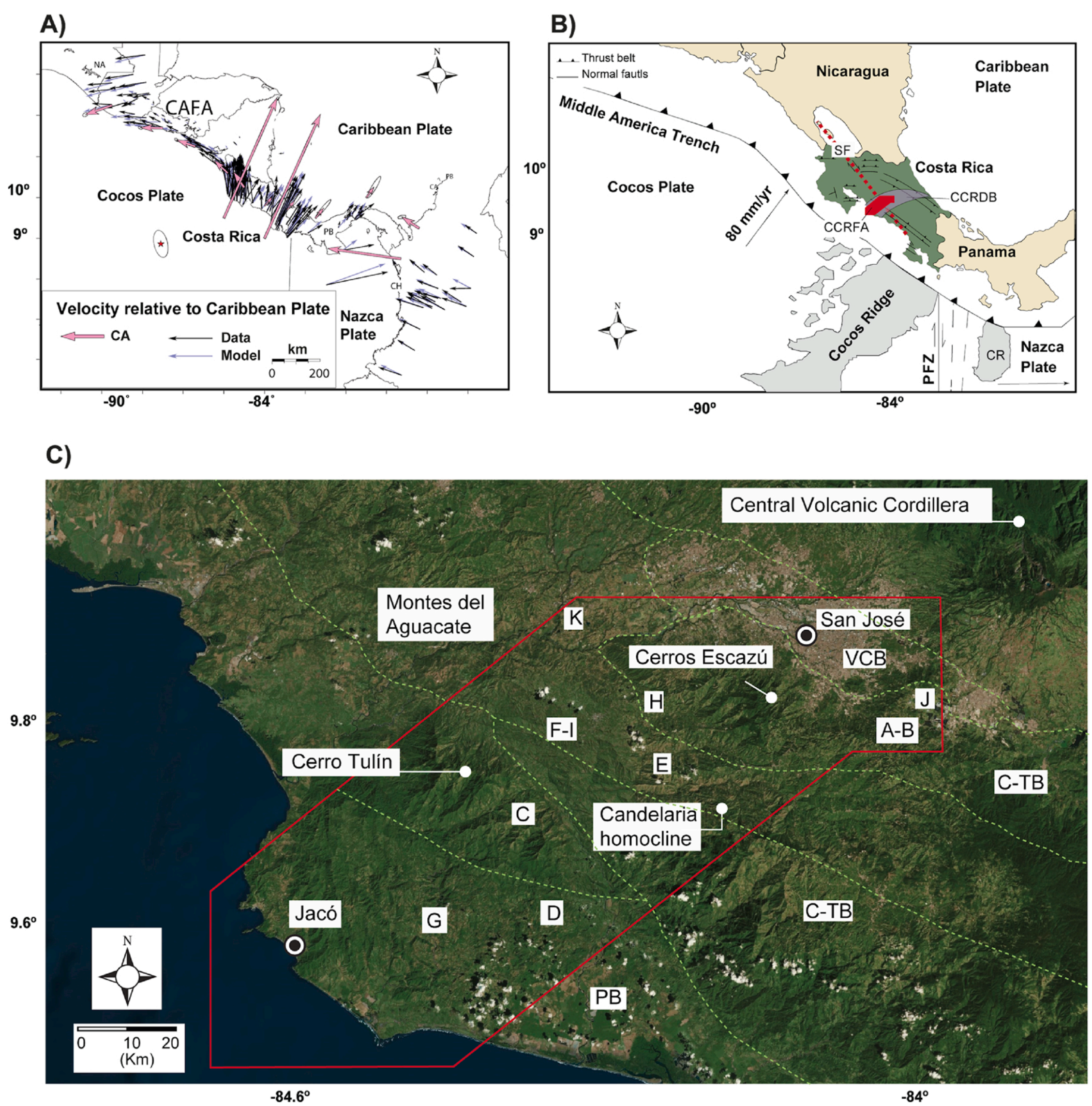

Fig. 1. A) Black and blue arrows, velocities relative to Caribbean Plate. Pink arrows indicate azimuth relative to Caribbean Plate (Kobayashi et al., 2014). B) Costa Rica tectonic setting (modified after Denyer and Alvarado, 2007). The red polygon marked CCRFA (Central Costa Rica ForeArc) is the study area. PFZ, Panama fracture zone. CR, Coiba Ridge. CCDB, proposed Central Costa Rica deformed belt. SF, Sliver fault. C) Central Costa Rica forearc showing main geographical features named in the text over Google Earth satellite image. Green dashed lines are the boundaries between the main morphostructural units. VCB: Valle Central basin; C-TB: Candelaria and Térraba basins; PB: Parrita basin. Inserted letters correspond to the location of the pictures in Fig. 4.

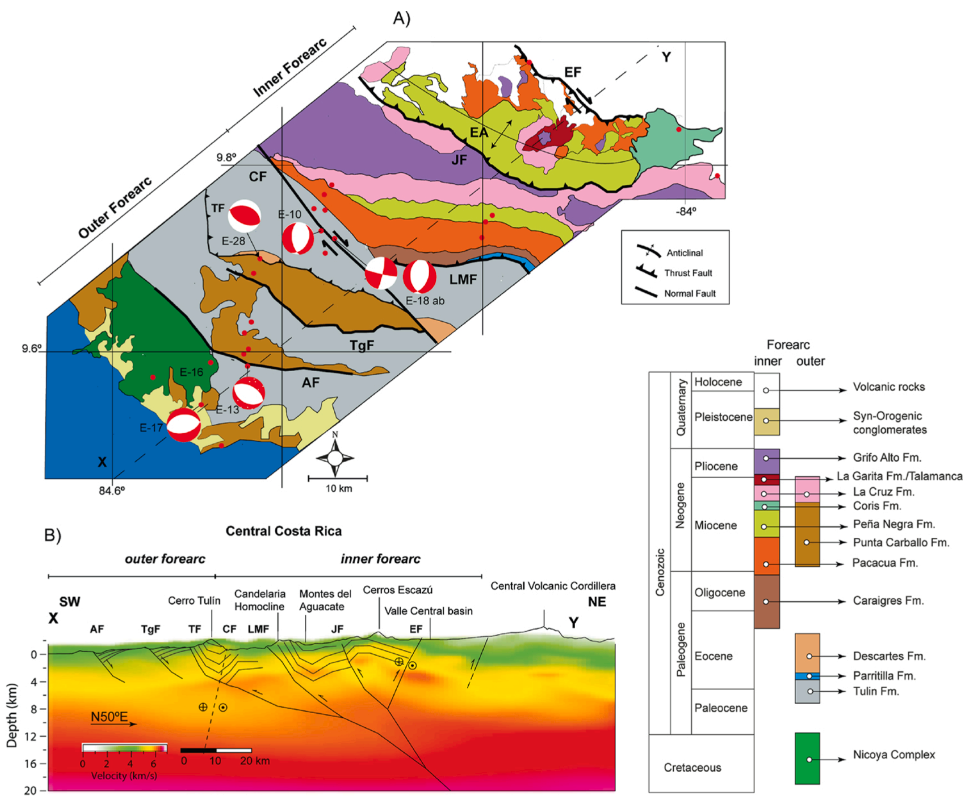

Fig. 2. A) Geologic map of central Costa Rica forearc (modified after Denyer and Alvarado, 2007). Red dots mark the location of data site stations. The focal mechanism-style "beach-balls" correspond to the solutions of kinematic analysis for major faults along the forerarc (see the text for details). AF: Angostura fault; TF: Tulín fault; TgF: Tigre fault; LMF: La Mesa fault; CF: Candelaria fault; JF: Jaris fault; EF: Escazú fault; EA: Escazu Anticline. B) Central Costa Rica inner forearc schematic cross-section, interpreted over seismic tomography velocity model of Hayes et al. (2013). In general, green represents low (<5 km/s) velocities, and high velocities (>6 km/s) are red. Labels for structure names are the same as Fig. 2A.

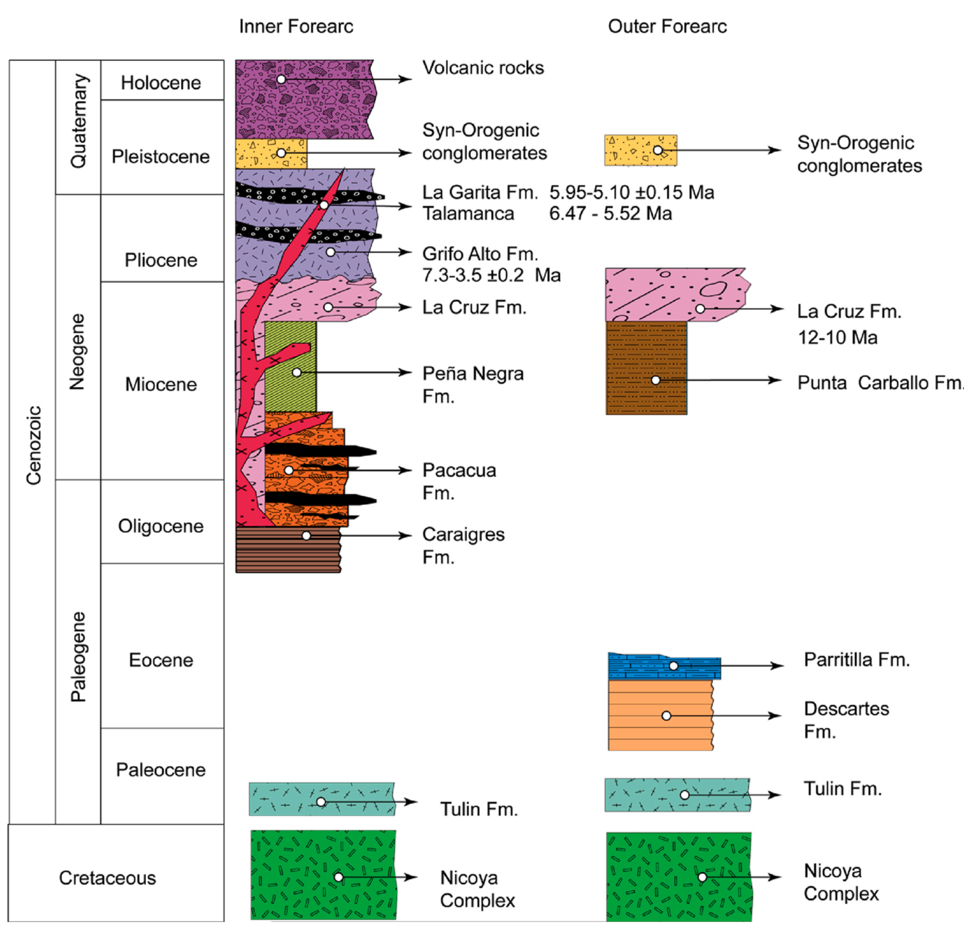

Fig. 3. Simplified Cenozoic lithostratigraphic stratigraphy of the Central Costa Rica forearc. (Denyer and Alvarado, 2007, and references therein).

Ar^{39}/Ar^{40} radiogenic ages of 83.2 ± 1.8 Ma (Sinton et al., 1997) and 86.0 ± 2.0 Ma (Hauff et al., 2000).

The Tulín Formation (Figs. 2 and 3) is dominated by vesicular pillow basalts with microdoleritic texture, which have been interpreted as rocks from a seamount with an ocean island basalt (OIB)-like signature (Arias, 2003). Epiclastic sediments, breccias, sandstones and tuffs are interbedded with the basalts (Denyer and Gazel., 2009). The record of large foraminifera and radiolaria suggest an oceanic shallow water environment of deposition. The above mentioned variety of rocks of the Tulín Formation are typically crosscut by quartz and epidote veins (Arias, 2003).

Tectonic emplacement of the Tulín Formation along the western margin of Costa Rica likely occurred in the middle Eocene, either as a beheaded oceanic island or as a block related to an ancient transform fault (Arias, 2003). Overlying by upper Eocene calcareous platform deposits, the Tulin Formation is constrained to the Maastrichtian-lower Eocene (Arias, 2003).

However, the contact between Nicoya Complex and the Tulín Formation is unclear to be either stratigraphic or tectonic (Tournon and Bellon, 2009).

2.2. Cenozoic sedimentary sequences

A series of sedimentary depocenters were formed along the southwestern margin of the Caribbean Plate during the Paleogene (Fig. 2; Astorga et al., 1991; Barboza et al., 1995). It is argued in many works that central Costa Rica sedimentary rocks are not associated with normal faults from the Paleocene onwards (e.g. Fisher et al., 2004; Sitchler et al., 2007; Denyer and Alvarado, 2007). In spite of this, several lines of evidence suggest that thick Cenozoic sequences were controlled by an extensional/transtensional regime based on stratigraphic, seismic reflection sections, and field mapping (Denyer and Arias, 1991; Astorga et al., 1991; Barboza et al., 1995; Brandes and Winsemann, 2018).

The outer forearc (Figs. 2 and 3) is characterized by Paleocene-Eocene turbidites of the Descartes Formation and Miocene shallow marine volcaniclastic sediments of the Punta Carballo Formation (Madrigal, 1970; Astorga, 1987) covering unconformably the Tulín Formation and Nicoya Complex (Denyer and Arias, 1991).

In the inner forearc (Figs. 2 and 3), the Oligocene massive breccias and sandstones of the Caraigres Formation are unconformably overlying the Tulín Formation (Bolz and Calvo, 2002). Moreover, these marine sequences are conformably covered by lower Miocene continental sandstones, conglomerates and volcaniclastic rocks of the Pacacua Formation (Denyer and Arias, 1991; Badilla et al., 1999).

An anoxic period in the middle Miocene deposited a succession of black shales, denominated Peña Negra Formation, product of a closed marine basin with low tidal influence (Obando et al., 1991). This unit grades towards the NE to coastal beach and swamp deposits of the Coris Formation (Obando et al., 1991).

2.3. Miocene-Pliocene volcanic sequences

During the Miocene two volcanic belts were established: a voluminous frontal arc denominated the Montes del Aguacate Group and the backarc volcanic belt of Sarapiquí, developed outside of the study area (Gazel et al., 2005; Bundschuh and Alvarado, 2007; Saginor et al., 2013). The Montes del Aguacate Group is comprised of two formations composed by eruptive rocks and by a number of intrusive bodies. The La Cruz Formation is a thick sequence of basic volcanic rocks, tuffs and intermediate pyroclastic deposits (Marshall et al., 2000; Alvarado and Gans, 2012) of Serravallian-Tortonian age (Table 1). Over this unit, separated by an angular unconformity, the Grifo Alto Formation is composed by andesitic rocks and tuffs with at least 650 m thickness (e.g., Bellon and Tournon, 1978; Amos and Rogers, 1983; Alvarado et al., 1992; Gillot et al., 1994; Marshall et al., 2000; Marshall et al., 2003; Gans et al., 2002, 2003; MacMillan et al., 2004; Alvarado and Gans, 2012), of late Miocene and Late Pliocene age (Table 1). Minor intrusions are coeval with this unit, like the Cerros de Escazú-Talamanca monzodiorite dated at 5.95 ± 0.05 Ma (Table 1). In addition to this, mildly alkaline hypabyssal basalts intruded La Cruz and Grifo Alto Formations as dykes and sills throughout the study area (Alvarado and Gans, 2012; Fig. 3). These rocks are grouped in La Garita Formation of Late Miocene age (Table 1). The source of these rocks has been related to mantle upwelling with minor subduction components (Hoernle et al., 2008; Gazel et al., 2009), and their alkaline geochemistry has been interpreted as an indication of an extensional environment during their emplacement (Alvarado and Gans, 2012).

Table 1
Miocene-Pliocene Volcanic Sequences.

Aguacate Group	Age (Ma)	Method	Reference
La Cruz Formation	12–10	$^{39}Ar/^{40}Ar$	MacMillan et al. (2004)
Grifo Alto Formation	7.3–3.5 ± 0.2	$^{39}Ar/^{40}Ar$	MacMillan et al. (2004) and Alvarado and Gans (2012)
Cerros de Escazú - Talamanca intrusive	5.95–5.10 ± 0.15	$^{39}Ar/^{40}Ar$	MacMillan et al. (2004) and Alvarado and Gans (2012)
La Garita Intrusive	6.47–5.52 ±	$^{39}Ar/^{40}Ar$	Marshall et al. (2003); Gazel et al. (2009); Alvarado and Gans (2012)

2.4. Pliocene- present day

A fissural magmatism created the Paleo-Central Volcanic Cordillera in the Central Costa Rica forearc (Alvarado and Gans, 2012; Protti et al., 1996; Kussmaul, 1988), along with the development of the Valle Central basin (Fig. 1). Since 2 Ma, the Cocos Ridge, an anomalously thick aseismic ridge derived from the Galapagos hot spot, comprises the southernmost ~200 km of the Cocos plate, it is subducting near--orthogonally under the Caribbean plate (DeMets et al., 1990; DeMets, 2001; Kellogg et al., 1995).

Currently, the GPS vectors show strong fault-parallel motion along the northern Costa Rica forearc that suggests a sliver motion (Feng et al., 2012; LaFemina et al., 2009). Montero et al. (2017) from neotectonic evidence trace a strong deformation zone in a NW-SE direction over the Cordillera de Guanacaste volcanic arc (Fig. 1a).

In the Central and Southern Costa Rica forearc, fault-parallel motion decreases and fault-perpendicular motion increases, illustrating greater convergence into the Central-Southern forearc (LaFemina et al., 2009), where current mountain building is observed (Fig. 1a).

3. Methods

In order to analyse the structure of the Central Costa Rica forearc, we integrate kinematic analysis of fault-slip data to characterize old deformation events and seismological data to provide information on the current deformation.

Fault-slip data were measured at 28 stations distributed throughout the study area (Fig. 2). Slickensides with fibrous crystal growth and Riedel shear fractures were used as kinematic indicators to determine fault-slip direction and sense (e.g., Petit, 1987). Slip on faults and shear fractures were measured to document movement on six main faults stations. Additional kinematic data were measured from outcrop-scale faults in 22 stations (Fig. 4). These data are helpful to understand the regional deformation field since large structures can be reactivated faults developed in previous deformation events, in which case the movement is constrained by their orientation. Fault-slip data were analyzed using FaultKin (Allmendinger et al., 2001) with the methods described by Marrett and Allmendinger (1990).

For the seismicity analysis, we used the database obtained by the Observatorio Vulcanológico y Sismológico de Costa Rica (OVSICORI) network. We analyzed data since 2010 considering that at that time the

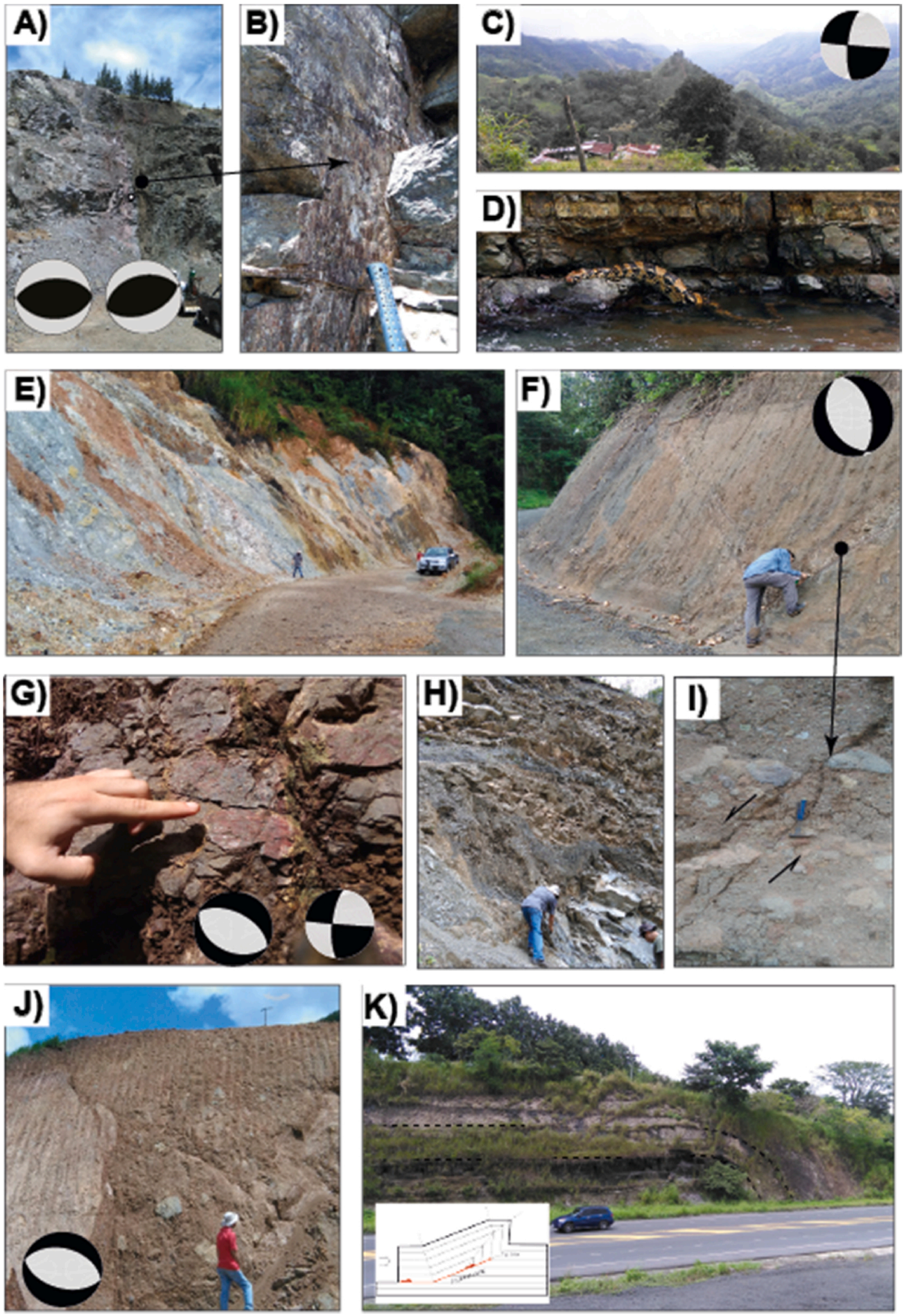

Fig. 4. Field photographs. See locations in Fig. 1.
A, B) Minor faults affecting the Pacacua Formation at a quarry denominated "Tajo El Volcán", in the inner forearc. Bedding is subvertical with E—W strike. C) Remanent butte associated with Candelaria fault at Salitrales. D) Undeformed sedimentary strata of the Punta Carballo Formation. E) Hydrothermal alteration associated with upper Miocene intrusions.F) The Jaris fault affecting the subhorizontal volcanic rocks of the La Cruz Formation in the inner forearc. G) Picture of slickenside with stepped slickenfibers in Tulín Formation.
H, I) Detail of the Jaris fault zone deforming pyroclastic deposits of the La Cruz Formation.
J) Minor faults affecting middle Miocene rocks of the Coris Formation in the inner forearc. K) Neotectonic NE-vergent fault-propagation fold on Pleistocene volcanic rocks close to the Río Grande toll, on the national route 27. The sketch shows the geometry of the fault-propagation fold.

OVSICORI network was upgraded with new instruments and digitizers. Focal mechanisms were calculated using the first polarities motions in the FOCMEC program (Snoke, 1984). We used the focal mechanisms derived from earthquakes with local magnitudes between 1.0 and 4.7 and clustered in different localities distributed throughout the study area. Afterwards, we used the PBT method implemented in the Win-Tensor software (Delvaux et al., 1997; Delvaux and Sperner, 2003) to process the focal mechanisms and obtain the local stress field for each zone.

The details of fault-slip data and seismicity analysis are presented in the Supplementary Materials.

4. Structure of the Central Costa Rica forearc

The overall structure of the outer forearc is characterized by outcrops of basement units and is dominated by strike-slip and normal faults. The inner forearc corresponds to the location of the thickest Cenozoic basins and the Montes del Aguacate magmatic arc. Normal, reverse and strike-slip faults are present in this sector (Figs. 1,2).

4.1. Structure of the inner forearc

The main faults in the inner forearc are the Mesa, Jaris and Escazú faults. These structures define narrow depocenters running WNW-ESE which are filled by the Miocene Pacacua and Peña Negra Formations

(Fig. 2).

The Mesa fault uplifts and folds the Cenozoic sedimentary sequences. The distribution of Miocene sediments indicates a strong control on the deposition by the Mesa fault. Northeastward from this structure, the Miocene rocks have a great thickness in the hanging wall, whereas towards the west these sequences are absent (Fig. 2).

Toward the east, the Jaris fault runs for over 25 km and is related to the thrusting of lower Miocene sedimentary rocks over upper Miocene volcanic rocks (Denyer and Arias, 1991; Denyer and Alvarado, 2007). The Jaris fault folds and overturns the beds of the uppermost part of the Peña Negra Formation. The fault damage zone is intruded by a series of dikes related to the Escazú-Talamanca diorite intrusion (Figs. 2 and 3).

The Escazú fault is an antithetic west-dipping structure, preserved at the surface in the NE flank of the Escazú anticline in the boundary between Cerros de Escazú and Valle Central. This fault is a west-dipping, ∽20 km long structure. Kinematic data from this fault, carried out by López (2012), indicate dextral-reverse motion, affecting the Miocene to Pleistocene strata, and partly covered by upper Pleistocene-Holocene deposits. The non-covered segments have been denominated by Montero et al. (2005) as; Escazú, Bello Horizonte, Aserrí, Patalillo, Río Azul and Agua Caliente faults.

The Escazu anticline has a NW-trending axis with moderate plunge towards the northwest, where the fold tightness decreases until the structure disappears. To the west, it corresponds to a highly asymmetrical west-vergent fold, associated with the Jaris fault. The Cerros Escazú area (Fig. 4) is interpreted in this work as an asymmetric southwest vergent anticline with a back-thrust in the hanging-wall corresponding to the Escazú fault.

4.2. Structure of the outer forearc

The outer forearc is affected by at least four west-verging basement-involving faults with high dips: Tulin,Tigre, Angostura and Candelaria faults.

The Candelaria fault zone can be found in the southwest of the study area, crossing the outer forearc and central zones as a NNW-striking structure, that truncates the thrust faults in the inner forearc. The Tulín fault thrusts the Tulín Formation over the Punta Carballo Formation.

Finally, the Tigre and Angostura faults determine the pattern of the Punta Carballo Formation which is surrounded by Tulín Formation and Caribbean Large Igneous Province rocks (Porras et al., 2019), suggesting that the Punta Carballo Formation was deposited in tectonic depressions.

5. Fault slip data

5.1. Major faults

We classified the kinematic indicators in two consistent solutions: (i) an event of extensional deformation with E—W stretching (n = 31, and Section 5.2), and (ii) a strike-slip solution (n = 12) with NE—SW stretching and NWS—E contraction, that indicates a dextral movement for the NW-striking Candelaria fault (Fig. 2).

The movement of the Candelaria fault was measured in two stations. The first one, station 18 (n = 60) corresponds to an outcrop with strong hydrothermal alteration. Minor faults within the fault zone display a wide range of orientations and movements, which reflect at least two different kinematic behaviours (Fig. 2). Based on the sense of slip, at the second station 10 (n = 10) six indicators can be explained by extension with E—W stretching. The other four correspond to reverse-oblique movements but cannot be integrated in a consistent solution.

Faults in the outer forearc show contrasting kinematics. The easternmost, the Tulín fault, exhibits reverse movement (station 28), thrusting basement rocks (Tulín Formation) over Miocene sediments of the Punta Carballo Formation. In contrast, the Tigre and Angostura faults show normal movement (Fig. 5). The data in stations 13 and 17 show a good fit and can be grouped within similar extensional kinematics. However, the Angostura fault at station 13 (n = 17) shows a normal movement with NE—SW extensional axis, consistent with the outcrop fault pattern. Furthermore, in station 17 (n = 13) the fault exposes a N—S extensional axis.

5.2. Minor faults

The outer forearc shows the most complex kinematic data, with normal, strike-slip and oblique normal/strike-slip faults. The minor faults are coated by a wide range of hydrothermal minerals precipitated during fault slip, which form stepped slickenfibers or, less commonly, non-fibrous infillings in strain fringes. Hydrothermal mineral fibers or infillings were found in different generations of low-temperature veins, composed by minerals such as epidote, chlorite and calcite. The complexity of the kinematic data is likely a result of the variations in the deformation conditions since the Late Cretaceous, the interaction between regional tectonics, and the earthquake cycle of the subduction megathrust (Astorga et al., 1991; Barboza et al., 1995; Mescua et al., 2017; DeShon et al., 2003). An extensional deformation event is widespread with a NE to E stretching direction (Figs. 5 and 6; stations 6, 7, 11A, 12B, 16, 27). This event is also observed in the inner forearc (Figs. 5 and 6; stations 3, 5, 21, 22). The youngest unit in which we recognize this extensional deformation is La Cruz Formation, although data for younger units is limited (Fig. 6). Some stations with extensional kinematics present N–S or NW stretching (Figs. 5 and 6; stations 20, 25, 26); this could be the result of local rotations of the stress field or vertical axis block rotations.

An event of contractional deformation with N to NE contraction is recorded throughout the study area (Figs. 5 and 6; stations 15, 19, 4). This event affects the Miocene intrusives at station 15, indicating its occurrence after the extensional event described in the previous paragraph. At station 4, a few data are inconsistent with the contractional event (3 out of 19 measurements), indicating that probably there is another deformational event that could not be determined from kinematic analysis.

Further, the outer forearc presents a complex pattern of faults consistent with strike-slip deformation in at least two different events. The first one, corresponding to NE stretching and NW contraction (Figs. 5 and 6; Stations 8, 11, 14, 23) and another with opposite kinematics are observed (Figs. 5 and 6; Stations 12, 16, 19, 26).

Notably, this strike-slip deformation event is not observed in the inner forearc minor faults, except for station 1, located less than 1 km away from the Escazú fault. Kinematic indicators for this station reveal a strike-slip deformation, with NW stretching and NE contraction. This is consistent with the right lateral movement indicated for the Escazú fault by López (2012), and we interpret that this station is showing the movement of this structure.

6. Present deformation, insights from seismicity

Most of the 250 earthquakes studied in the forearc are shallower than 20 km and are concentrated in the inner forearc (Fig. 7). The hypocenter locations range from 5 to 10 km of depth near the Jaris and Escazu fault and increase depth towards the east under the Valle Central basin, where the seismicity is located at 20 km depth.

Based on the spatial distribution, the seismicity was grouped in 6 zones (Fig. 7) according to Vega et al. (2018); Fernández and Montero (2002), and Quintero and Porras (2019). The composite focal mechanism solutions obtained in this study spans strike-slip, normal and oblique faulting combining strike–slip and dip-slip motion. We assume that for each zone, all the seismic activity took place within the same stress state, and therefore we can use the focal mechanisms to carry out a stress inversion that represents the current stress state in each of the zones.

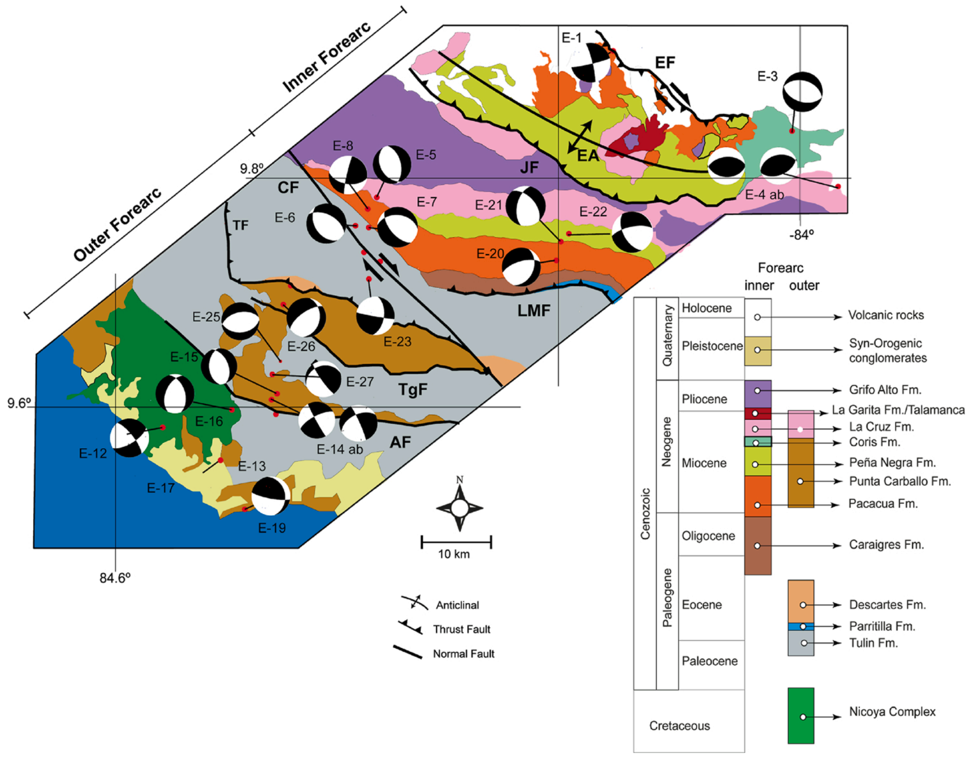

Fig. 5. Kinematics of faults along the forerac. The forearc shows normal, strike-slip, oblique normal/strike-slip faults and contractional.Red dots are the location of station with the station name (e.g. E-10) and best fit solution.

Most solutions exhibit a strike-slip stress state, with the average direction of minimum stress (σ_3) near WNW-ESE, and the maximum stress (σ_1) trending NNE-SSW (Fig. 7). Locally, some zones show a compressional (zone 6, Fig. 7) or extensional stress state (zones 2 and 3, Fig. 7). The variability of the focal mechanisms may reflect spatial heterogeneities in the stress field, or variations in fault orientations subjected to a uniform strike-slip stress field.

For example, local extension may result from bends of the Jaris and Escazú faults with dextral strike-slip movements on these structures, in the Cerros de Escazú sector.

Therefore, stress inversion of focal mechanisms reveals that the present-day strain occurs under a transpressive regime in the inner forearc, particularly in the Escazú anticline, consistent with neotectonic studies by López (2012).

7. Structural evolution

7.1. Paleogene- early Miocene extensional regime

We can distinguish at least one extensional episode during the early Cenozoic (Fig. 8), well documented in minor faults throughout the forearc and fossilized on major faults in the outer forearc. Thickness and facies changes in the pre-middle Miocene units are controlled by regional NE trend extension with NW—SE striking normal faults. In the outer forearc, the extensional episode affected the basement and likely controlled the deposition of the Punta Carballo Formation (Fig. 8). The extensional regime also affected the inner forearc and controlled deposition of the Paleocene-Miocene series. Based on the age of syn-extensional units, the NE—SW extensional regime started at least in the Paleocene and continued up to the early Miocene. Similar evidence is described by Brandes and Winsemann (2018), where they interpret the late Eocene to Early Oligocene deformation as a complex uplift and subsidence pattern implying an oblique subduction. The Miocene rifting episodes and the extension directions postulated for the forearc by previous works (Astorga et al., 1991; Obando et al., 1991; Barboza et al., 1995; Porras et al., 2019) are in agreement with the data presented here.

7.2. Middle Miocene contractional regime

During the middle-late Miocene, the central forearc recorded a NE-SW compressional tectonics registered in minor faults involving dikes of La Cruz and La Garita Formations. Several previous works confirmed that most of the region was affected by a middle to late Miocene event of contractional deformation (Ballestero et al., 1995; MacMillan et al., 2004; Brandes et al., 2007; Mescua et al., 2017).

The Jaris fault, acted as a thrust that moved the pre-middle Miocene sedimentary units over the Upper Miocene-Pliocene volcanic sequences. To the SW, this contractional episode is responsible for Mesa fault and the subsequent Candelaria homocline. This compression is focused in the inner forearc, where the Jaris thrusts and Escazú backthrusts are developed and the Escazú anticline grows (Fig. 8).

7.3. Pliocene to present day transpressive regime

Fault-slip data and seismicity suggest a significant change in kinematics throughout the forearc from the middle Miocene-Pliocene compression to the Pliocene-Recent transpressive system (Fig. 8). This change is observed in the kinematics of major faults (Fig. 2), like the Candelaria and Escazu Faults which show strike-slip kinematics as documented in our fault-slip data and in previous works (López, 2012). At surface, the Escazu fault achieves a small amount of shortening and does not tilt nor fold the upper Miocene formations. Displacement decreases toward the NW and associated Quaternary deformation is observed folding the Pleistocene volcanic rocks (Tiribi Formation).

Strike-slip kinematics has not been observed in minor faults in the inner forearc, suggesting that this deformation was focused on major pre-existing faults.

The analysis of seismic activity, using the inversion of the focal mechanisms, indicates a strike-slip regime with WNW-SSE trending σ_3 stress axis.

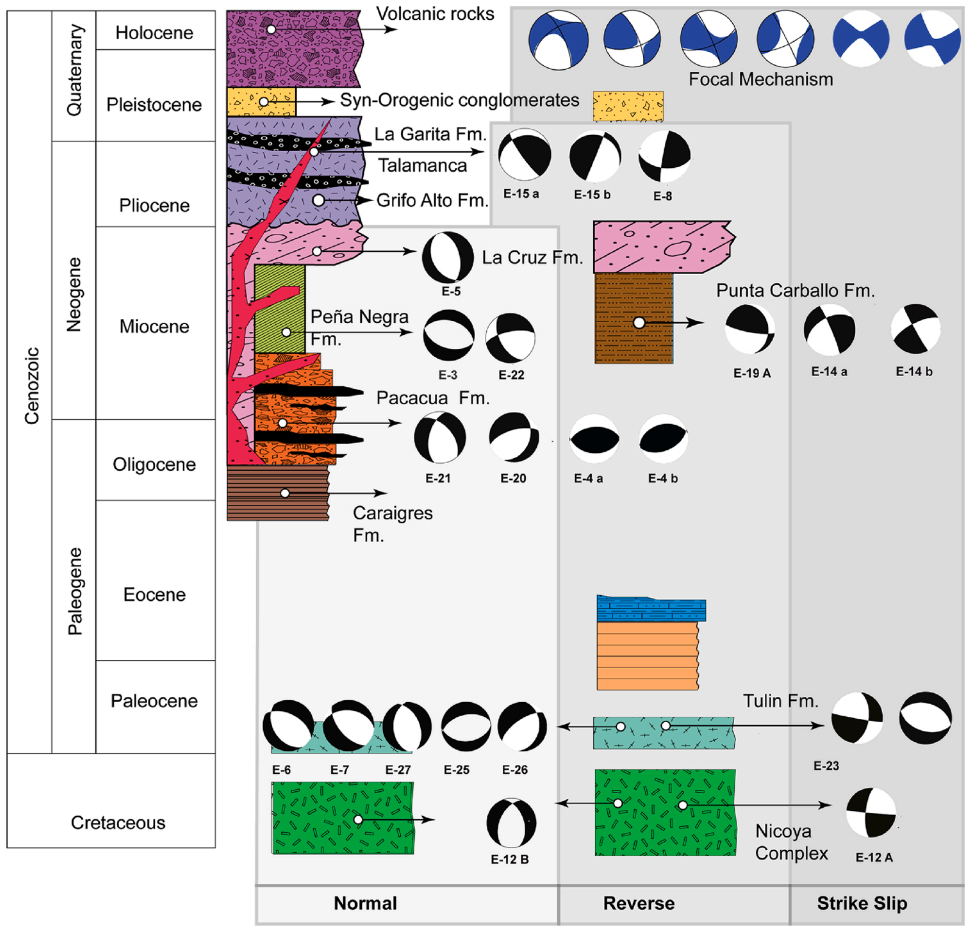

Fig. 6. Different phases of kinematics sense through time in Central Costa Rica forerac geologic formations. Focal mechanism from Vega et al. (2018).

8. Discussion

8.1. Tectonic controls on upper plate deformation patterns

The results presented in this work suggest that in terms of crustal deformation there are three major tectonic periods in the Neogene in the Central Costa Rica forearc: (i) the first period (Fig. 8) is characterized by an extensional regime with the inception of normal faulting throughout the forearc. The onset of this regime took place in the Paleocene and continued up to the early Miocene; (ii) the second period started shortly after 12 Ma, and was marked by a change to crustal shortening, with the development of reverse faults and folds (Fig. 8). These were restricted to the inner forearc and coincided within the regional uplift and the end of extensional basin development; (iii) the third period involved cessation of crustal shortening along the central Costa Rica forearc and a change in style of strain from reverse to strike-slip displacement during the Pliocene (Fig. 8).

Different mechanisms have been proposed to account for changes in styles of faulting on the forearc.

Brandes and Winsemann (2018) proposed that changes in deformation styles during the Cenozoic are controlled by the alternation between slab rollback and flat slab periods, that would have controlled the evolution of sedimentary basins since the Paleocene (Brandes and Winsemann, 2018 and references therein). This model suggests an extensional phase during the Maastrichtian to Oligocene, characterized by rapidly subsiding sedimentary basins, and deposition of thick arc-derived volcaniclastic material in a setting dominated by slab rollback. The onset of the contractional phase during the Neogene in southern Costa Rica is interpreted by these authors as the result of a shallower subduction angle (Brandes and Winsemman, 2018). A second mechanism, acting since the Pliocene, involves the arrival of the Cocos Ridge at the Middle America trench (Gardner et al., 1992; Abratis and Wörner, 2001; Morell, 2016, 2019). The observation that the greatest shortening and highest elevations of the Talamanca range are located directly inboard of the Cocos Ridge axis suggests that contraction in this sector, south of the study area, is controlled by the collision of the Cocos ridge against the trench (Fisher et al., 2004; Sitchler et al., 2007; Morell et al., 2013).

Mescua et al. (2017) propose that the main control on deformation is related to variations in the direction of convergence between the plates and in particular, to the obliquity between the subducting plate and the margin (Fig. 8). Changes in the angle of convergence have been proposed to produce forearc stretching or contraction (McCaffrey, 2009). Based on the reconstruction of the development of oceanic expanding centers (Meschede et al., 1998; Meschede and Barckhausen, 2000; Barckhausen et al., 2008), 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 subduction probably led to the development of strike-slip and normal fault systems subparallel to the margin (Fig. 8). 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, produced the change to a NNE movement of the Cocos plate, producing orthogonal subduction along the Middle America trench (Meschede et al., 1998). Therefore, orthogonal convergence between the Cocos plate and the Middle America trench took place along the Costa Rican sector of the trench during the Miocene, with the development of a contractional episode (Mescua

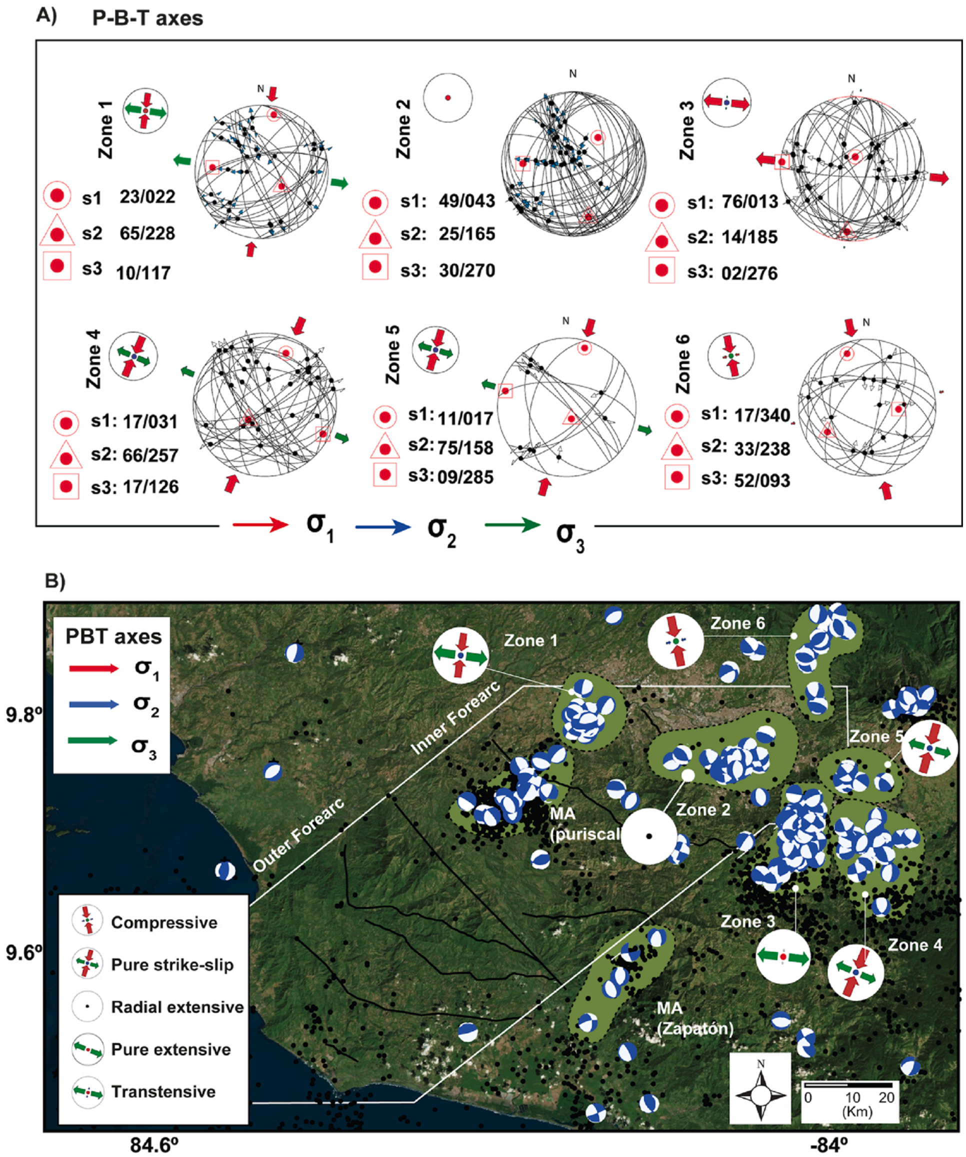

Fig. 7. Seismicity distribution from 2010 to 2017. A) P-B-T axis method of stress inversion from focal mechanisms. Lower hemisphere equal-area stereoplots of selected focal planes with the three principal stress axis. Horizontal stresses (SH_{max} and SH_{min},) distribution of uncertainties, and σ_1 standard deviation of the SH_{max} directions. Stress symbols show the horizontal stress axes (SH_{max} and SH_{min}), as a function of the stress ratio R. Green outward arrows: σ_3 stress axis, blue arrows: σ_2 stress axis, and red arrows: σ_1 axis. The vertical stress (σv) is shown as a solid circle: green for extensional regimes ($\sigma_1 \sim \sigma_v$), blue for strike-slip regimes ($\sigma_2 \sim \sigma_v$), or red for compressional regimes ($\sigma_3 \sim \sigma_v$). B) Seismicity and focal mechanisms in the Central Costa Rica Forearc. White line indicates the study area. Black lines are the main faults mapped in the study area. Black dots show the epicenter of seismic events. Zones 1 to 6 correspond to the regions analyzed to obtain stress states.

et al., 2017). This contractional phase is observed in faults affecting Miocene sedimentary rocks and minor intrusions, coeval with the Cerros de Escazú monzodiorite dated at 5.95 ± 0.05 Ma ($^{40}Ar/^{39}Ar$, Alvarado and Gans, 2012) and 5.10 ± 0.10 Ma ($^{40}Ar/^{39}Ar$, MacMillan et al., 2004) and La Garita Formation dykes and sills throughout the study area, dated between 6.47 and 5.52 Ma $^{40}Ar/^{39}Ar$ (Marshall et al., 2003; Gazel et al., 2009; Alvarado and Gans, 2012). This change in convergence angle might produce a change in subduction angle as proposed by Brandes and Winsemann (2018), although the evidence for an event of shallow or flat subduction is limited.

The present movement of the Cocos plate is still toward the NNE, roughly orthogonal to the Middle America Trench. However, a change to a strike-slip regime is observed in the Central Costa Rica forearc since the Pliocene, as recorded by GPS and seismic data in the inner forearc along with the development of a north-moving (sinistral) sliver in the outer forearc (Lewis et al., 2008; Montero et al., 2017). This setting might correspond to transition between the extensional segment of the Middle America trench to the northwest in Nicaragua (Fig. 8 and inset in Fig. 1a), dominated by slab rollback (Dewey and JF, D., 1980; Morgan et al., 2008; Ramos, 2010), and the subduction of the Cocos ridge to the southeast that produces contraction in the upper plate (MacMillan et al., 2004; Sitchler et al., 2007; Morell, 2016).

We propose that the evolution of the Central Costa Rica forearc is the result of the combination of the last two proposed mechanisms: (i) changes in the obliquity of subduction and (ii) changes in the dynamics of the slab since the arrival of the Cocos Ridge at the Middle America trench in the Pliocene.

9. Conclusions

We analyze the tectonic evolution of the Central Costa Rica forearc using structural and seismological data. Our results underscore the complex variations in deformation in the region through the Neogene times. The Paleogene to middle Miocene are characterized by extensional basins, with the development of normal faults in a setting of oblique convergence. An important reconfiguration of the stress field occurred during the orthogonal subduction in the middle-upper Miocene, leading to basin inversion with the development of fold and thrust belts

The variability in the structural style during these times seems to be strongly controlled by the convergence obliquity changes between the Coco and Caribbean plates.

Since Pliocene time, the change to a strike-slip regime coincided with the collision of the Cocos Ridge against the southern Costa Rica margin

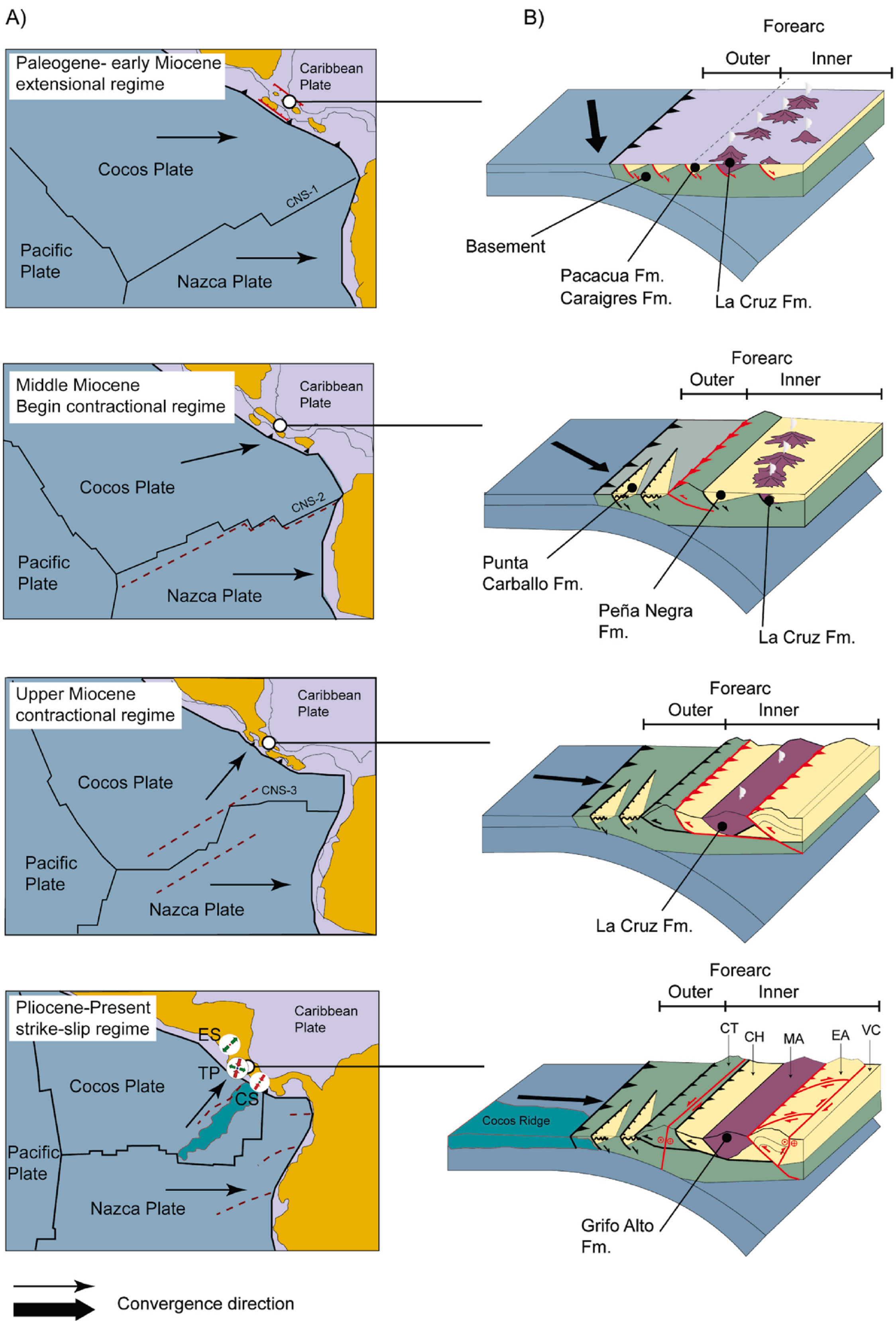

Fig. 8. a) Tectonic evolution of the Cocos Plate (Meschede and Barckhausen, 2000). Dotted red line is the distribution of extinct spreading systems boundaries from Meschede et al. (1998). b) Schematic evolution block diagram of the central Costa Rica forearc. C.S., Contrational segment; E.S., Extensional segment; CT, Cerro Tulín; CH, Candelaria Homocline; MA, Montes del Aguacate; CE, Cerros Escazú; CV, Valle Central basin, EA, Escazú Anticlinal. Active faults are shown in red lines.

and can be associated with the northwestward extrusion of the forearc block.

Authorship statement

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, each author certifies that this material or similar ma-terial has not been and will not be submitted to or published in any other publication before its appearance in the Journal of Geodynamics.

Declaration of Competing Interest

The authors whose names are listed immediately below certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as hono-raria; educational grants; participation in speakers' bureaus; membership, employment, con-sultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, af-filiations, knowledge or beliefs) in the subject matter or materials discussed in this manu-script.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.jog.2020.101814.

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