



Overview of the Tectonics and Geodynamics of Costa Rica

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Abstract

Although Costa Rica is a relatively small region along the Central American Volcanic Arc (CAVA), its fascinating geology records several interesting examples of recent arc evolution. The forearc at present is in a state of subduction erosion, ranging from ‘moderate’ long-term rates of $\sim 100 \text{ km}^3/\text{km}/\text{Ma}$ beneath Nicoya Peninsula to ‘extreme’ short-duration peaks of $\sim 1,000 \text{ km}^3/\text{km}/\text{Ma}$ beneath Osa Peninsula. The margin is currently both seismogenic and tsunamogenic, with seismicity nucleating along one of Earth’s shallowest seismogenic plate interfaces. Here, arc volcanism has created much larger volcanic edifices than it has northward along the CAVA. Forearc deformation is ongoing and active, and associated with large-scale erosion and sediment transport towards the trench that is currently being almost entirely trapped in forearc basins prior to the trench axis. Margin evolution is also strongly linked to documented spatial and

temporal variations in the incoming Cocos and Nazca Plates. These conditions have had significant consequences for the geochemical evolution of the CAVA in Costa Rica, so that Costa Rica’s active geology records one of Earth’s most diverse and interesting volcanic arcs.

Keywords

Costa Rica • Cocos plate • Caribbean plate • Osa Peninsula • Geodynamics

1 Introduction

Costa Rica sits at the south-east end of the $\approx 1,500 \text{ km}$ —long Central America convergent margin. The Cocos plate subducts with a convergence direction $\text{N}25^\circ\text{--N}30^\circ\text{E}$ with respect to the overriding Caribbean Plate at rates varying between $83 \text{ mm}/\text{yr}$ in northern Costa Rica and $93 \text{ mm}/\text{yr}$ in southern Costa Rica (DeMets et al. 1990; DeMets 2001) (Fig. 1). The Central America Trench ends in southern Costa Rica against the Panama Fracture Zone, which marks the boundary with the Nazca plate, and forms a triple junction between the Cocos, Nazca, and Caribbean Plates. The central Costa Rica to Panama region of the Caribbean spans four converging tectonic plates: South America,

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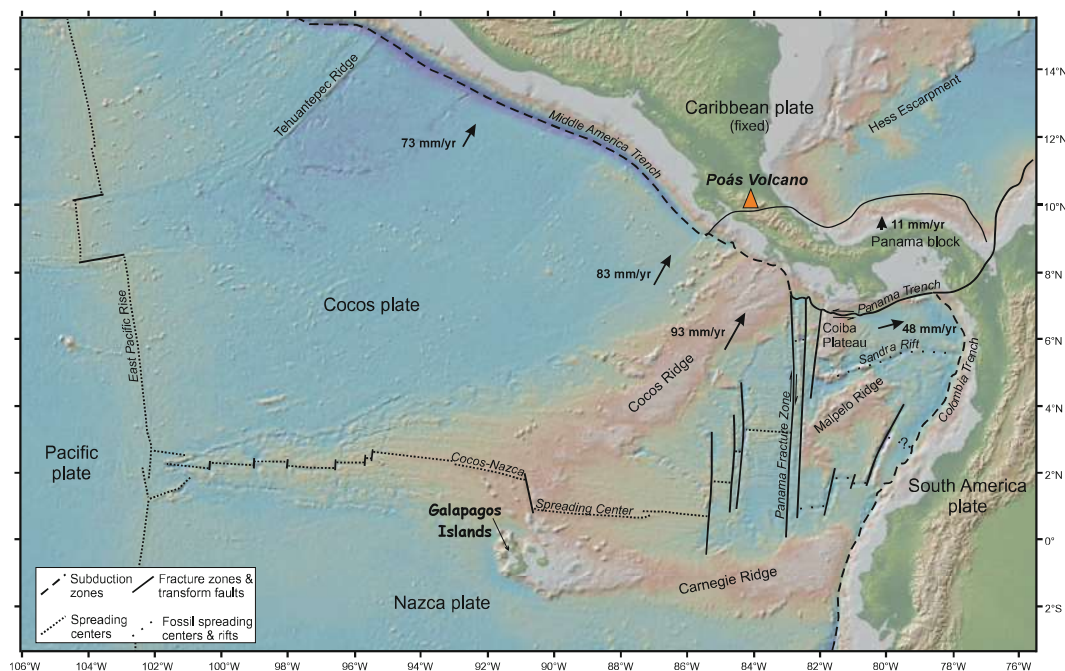


Fig. 1 Bathymetry, topography (<http://www.geomapapp.org> (Ryan et al. 2009)), and tectonic plate configuration in the region surrounding the Costa Rica. Arrows show plate motions with respect to the Caribbean plate (DeMets et al. 1990; DeMets 2001). Black dashed lines indicate trenches, black dotted lines indicate spreading centers, black solid lines indicate either transform faults, fracture zones or slow diffuse plate boundaries

Cocos, Nazca and the Caribbean itself (Fig. 1). The result is that this region has evolved as an independent lithospheric fragment, the Panama block, where plate motion is partitioned across a network of diffusive plate boundaries (Vergara Muñoz 1988; Marshall et al. 2000; DeMets 2001). The current motion of the Panama block is 11 mm/yr to the N with respect to the Caribbean Plate (DeMets 2001) (Fig. 1).

Poas Volcano is part of the NW-trending Central American volcanic arc (CAVA). In Costa Rica it extends from Orosí volcano to the NW to Turrialba volcano to the SE (Fig. 2). Between Nicaragua and Costa Rica the CAVA is offset 40 km to the SE, while a 175 km volcanic gap separates the Turrialba volcano from the Barú volcano in Panama, the last CAVA volcano to the SE (Fig. 2).

2 The Cocos Plate

During the early Neogene, the formation of the Galapagos rift system and the subsequent development of the Cocos-Nazca Spreading system (CNS) split the long-subducting Farallon plate into the Nazca and Cocos plates (Lonsdale 2005). The Cocos plate is formed at the East Pacific Rise (EPR) (Fig. 1), and at the present-day Cocos-Nazca Spreading system CNS-3. Detailed mapping of magnetic anomalies, in fact, shows two precursor spreading configurations CNS-2 and CNS-1 that imply a non-steady orientation of the CNS through time (Barckhausen et al. 1998, 2001). EPR- and CNS-crust are morphologically very different: EPR-crust is smooth and extensively cut by

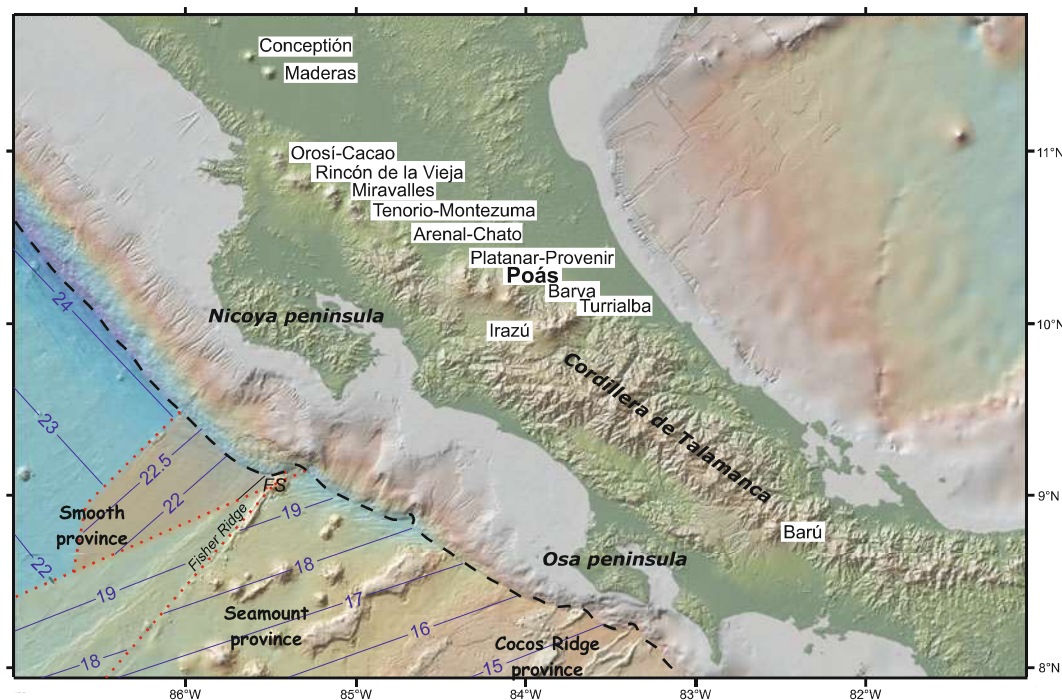


Fig. 2 Locations of volcanoes in Costa Rica and adjacent regions. Offshore Costa Rica shows a Cocos plate isochron map with ages derived from identification of seafloor spreading anomalies (Barckhausen et al. 2001). In blue is the crust generated at the East Pacific Rise, in

red, orange and yellow the crust generated during the different stages of Cocos-Nazca spreading center activity. Numbers indicate crustal ages in m.y. Smooth, seamount and Cocos Ridge provinces are also indicated. FS is Fisher Seamount

faults occurring at intervals of ≈ 300 km generated at the ridge and reactivated at the outer-rise; CNS-crust is heavily impacted by the Galapagos hotspot activity producing a morphologically rough seafloor constellated by seamounts and the relatively buoyant Cocos Ridge (Fig. 1). Offshore Costa Rica seafloor morphology is so distinctive that it can be divided into three provinces (von Huene et al. 1995, 2000) (Fig. 2): (1) a smooth segment off north-eastern Costa Rica, (2) a seamount-dominated segment off central Costa Rica, and (3) a Cocos Ridge segment off south-eastern Costa Rica. The three provinces are also characterized by a different structure in the overlying subduction zone.

(1) The smooth province is bounded by Fisher Seamount and Fisher Ridge to the south (Fig. 2). At the trench, the crust breaks into the normal faults mentioned above and

trends sub-parallel to the trench as effect of plate bending (Ranero et al. 2004). A narrow ridge offshore the central Nicoya Peninsula marks the EPR-CNS crust boundary (Barckhausen et al. 2001) with an age jump of the subducting oceanic crust from 24 Ma in northern Costa Rica to 21.5 and 22.5 Ma of the CNS-1 (Fig. 2).

(2) The seamount-dominated segment goes from south-east of the Nicoya Peninsula to the north-west of the subducting Cocos Ridge and it is 40% covered by seamounts (von Huene et al. 1995). The crust offshore central and south-eastern Costa Rica formed at the CNS-2 and has crustal ages between 19 and 15 Ma in the south (Barckhausen et al. 2001) (Fig. 2). Deep furrows and domes in the continental slope characterize the forearc slope of the seamount domain in Central Costa Rica indicating seamount subduction

(von Huene et al. 2000). This portion of the margin has generated up to M7 EQs that have been linked to the subducting seamounts (Husen et al. 2002).

- (3) Moving to the southeast the Cocos Ridge subducts beneath the Osa Peninsula in the south of Costa Rica. Where the Cocos Ridge subducts, the Middle America Trench—MAT—shallows from 4,000 m in the north of Costa Rica to less than 1,000 m deep offshore the Osa Peninsula which lies above the subducting Cocos Ridge (Fig. 2).

Where it currently subducts, the Cocos Ridge is 13–14.5 Ma (Werner et al. 1999; Barckhausen et al. 2001) and it is one of the two complementary ‘near-ridge’ hot spot traces of the Galapagos Hotspot, the other being the Carnegie ridge on the Nazca plate, formed because the intervening CNS has persistently remained astride the Galapagos hot spot (Fig. 1) (Morgan 1978). The Cocos Ridge lies $\approx 2,000$ m above its adjacent seafloor. Its plume-influenced oceanic crust reaches a thickness of 21 km along the crest of the ridge off Osa Peninsula (Stavenhagen et al. 1998; Walther 2003). To the east, the Panama Fracture Zone (PFZ) cuts the Cocos Ridge at the trench limiting its subducted extent to ~ 100 km inward from the trench (Protti et al. 1995). Here the Panama “Fracture Zone” is actually a right-lateral transform fault that is the current boundary between the Cocos and Nazca plates. East of where the PFZ intersects the trench axis, the Nazca Plate is moving to the east (N80°) towards South America where it subducts, so that this section of the Panama margin has relatively small deformation (Fig. 1).

Because the axis of the Cocos Ridge is oriented $\sim 10^\circ$ counterclockwise from the Cocos-Caribbean convergence vector (DeMets et al. 1990), it migrates slowly to the northwest along the MAT while the Panama Triple Junction migrates to the southeast (MacMillan et al. 2004; Morell et al. 2008). It has been proposed that the Panama Fracture zone truncated the Cocos Ridge around 9 Myr ago, with the Malpelo Ridge on the Nazca plate being the dislocated segment that

records this truncation (Hey 1977; Lonsdale and Klitgord 1978).

The triple junction migration and the subduction of the relatively buoyant Cocos Ridge has been playing a significant role in the deformation of the Costa Rican forearc producing a ~ 350 -km-long trench embayment culminating at the ridge axis where it is ~ 60 -km-wide (von Huene et al. 2000; Vannucchi et al. 2013) (Fig. 1).

The plate interface is strongly coupled between the Cordillera de Talamanca and the Osa Peninsula (Fig. 2) (Norabuena et al. 2004; LaFemina et al. 2009). This contributes to infrequent, large earthquakes (Protti et al. 2001; Norabuena et al. 2004), for example the April 3, 1983 ($M_s = 7.3$; depth = 30 km) plate boundary thrust event located beneath the forearc inboard of the Osa Peninsula (Adamek et al. 1987), and the April 22, 1991 ($M_s = 7.5$; depth = 12 km) back-thrusting event, located ~ 100 km beneath the back-arc (Tajima and Kikuchi 1995).

Segments of the plate interface adjacent to these coupled regions experience frequent, smaller earthquakes (Protti et al. 2001; Bilek et al. 2003; Bilek and Lithgow-Bertelloni 2005). Most of the seismicity is rather shallow and strongly associated with the incoming bathymetry focusing on the incoming seamounts and faults (Bilek et al. 2003; Arroyo et al. 2014). Inboard the Cocos Ridge, the upper plate shortens considerably across the Fila Costeña thrust belt, and the regional uplift with extinction of the volcanic arc in the Cordillera de Talamanca has been used to support the currently preferred hypotheses that there has been flat subduction of the buoyant Cocos Ridge (Kolarksky et al. 1995; Protti et al. 1995; Fisher et al. 2004; Sitchler et al. 2007). Recent seismological investigations, however, show evidence of a subducted portion of the Cocos Ridge no longer than 100 km, in accordance with plate tectonic reconstructions (Protti et al. 1995), followed by a steep slab (Arroyo et al. 2003; Dinc et al. 2010; Dzierma et al. 2011). It is worth noticing that in this scenario the uplift of the Cordillera de Talamanca would not be directly caused by subduction of

the Cocos Ridge as in this geometry Cocos Ridge material does not lie beneath the Talamanca.

Several dates have been suggested for the initiation of the subduction of the Cocos Ridge ranging from: 0.5 Myr based on elastic deformation studies (Gardner et al. 1992), 1 Myr based on ocean floor magnetic anomalies and plate reconstructions (Lonsdale and Klitgord 1978), 2–3 Myr from plate reconstructions (MacMillan et al. 2004; Morell et al. 2008), 3.6 Myr from on-land work on the Caribbean zone of Costa Rica (Collins et al. 1995), 5 Myr because of a sharp change in volcanic chemistry (De Boer et al. 1995), 3.5–5 Myr from thermochronological studies on the Talamanca batholiths to constrain the uplift of the Cordillera de Talamanca (Grafe et al. 2002) and 8 Myr from the end of arc volcanism in the Cordillera de Talamanca (Abratis and Worner 2001). Recent drilling offshore Osa peninsula—IODP Exp. 334 and 344—revealed a rapid event of

extreme subsidence of the forearc that has been interpreted as the direct damage caused by the onset of subduction of the Cocos Ridge at ≈ 2.2 Myr (Vannucchi et al. 2013).

2.1 Slab Imaging and Crustal Structure

The overall geometry of the Wadati-Benioff changes from Nicaragua to southern Costa Rica (Protti et al. 1995). Under the Nicaragua-Costa Rica border the seismic slab dips about 84° and reaches a maximum depth of 200 km. In central Costa Rica the seismicity is concentrated at 15 to 25–30 km depth defining a 18° dipping plate boundary (Husen et al. 2003) (Fig. 3), increasing to about 65° to a depth of 125 km. In southern Costa Rica the seismic slab seems to disappear below 50 km depth. However recent tomographic and receiver function investigations were

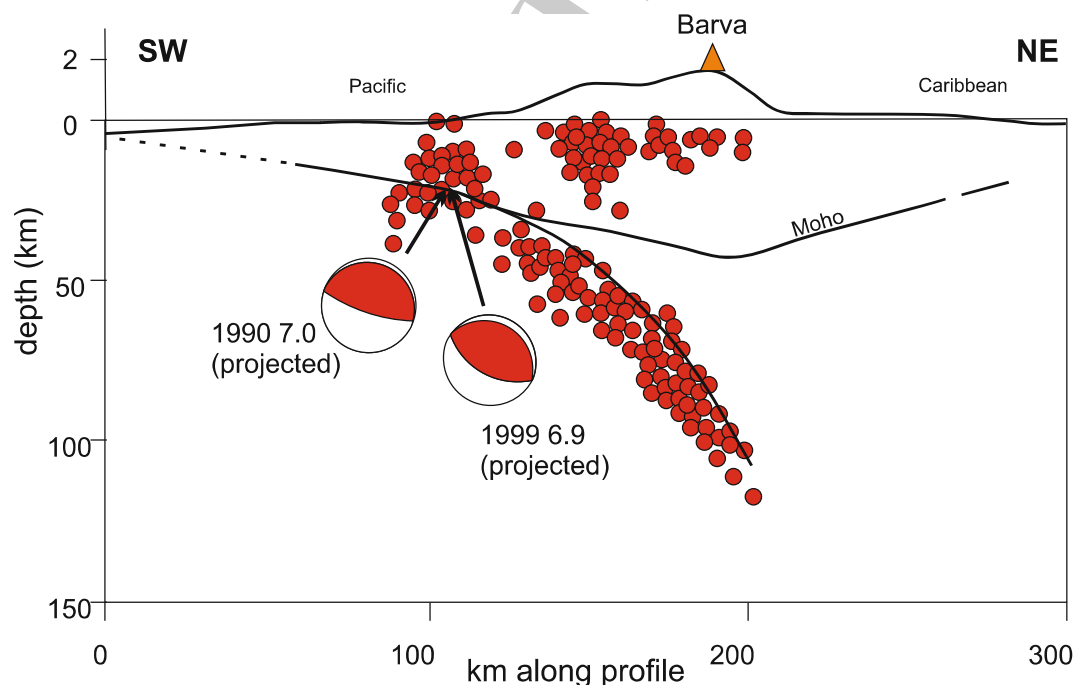


Fig. 3 Vertical section parallel to the dip of the subducting Cocos plate in the seamount-dominated segment off central Costa Rica. This section is coincident with the wide-angle seismic transect TICO-CAVA (Hayes et al. 2013—see Fig. 4 for location). The TICO-CAVA

data constrain the crust and crust-mantle transition beneath the volcanic arc. Seismicity and slab depths are taken from Husen et al. (2003). Fault plane solutions of two large events within this area are also projected onto the section

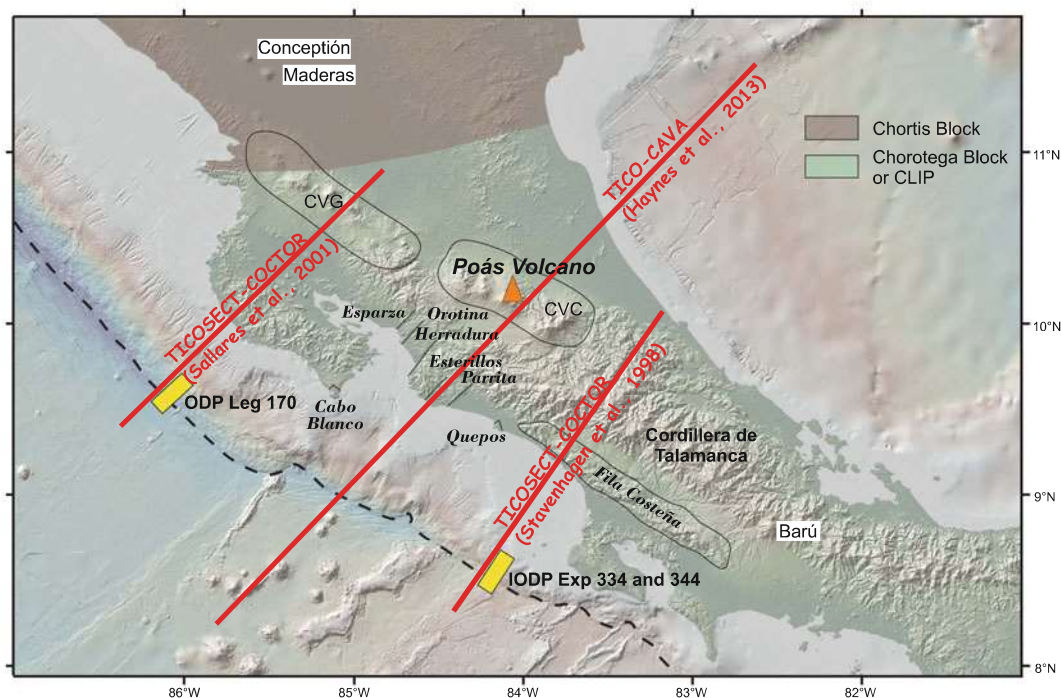


Fig. 4 Location of wide-angle seismic transects and ODP-IODP drilling expeditions discussed here. Named black line segments mark near-vertical faults perpendicular to the trench that dissect the margin in the central portion of the onshore forearc. To the south, where the Cocos Ridge subducts, the forearc is deformed in a fold-and-thrust belt—the Fila Costeña. Different

cordilleras defining the Central American Volcanic Arc in Costa Rica: Cordillera Volcánica de Guanacaste (CVG) and the Cordillera Volcánica Central (CVC). Chorotega (green) and Chortis (grey) basement sections of the Caribbean plate are indicated by different background shadings

able to show a well-defined steep slab with dips varying from 50–55° at depths of 40–60 km— (Dinc et al. 2010; Arroyo et al. 2014) to ~80° at ~100 km below the coastline (Dinc et al. 2010).

Tomographic studies have focused both on imaging shallow features, such as subducting seamounts (Husen et al. 2002, 2003), and on slab imaging below the Nicaragua-Costa Rica border (Syracuse et al. 2008; Arroyo et al. 2009).

Seismic wide-angle data were also acquired along onshore-offshore transects to define the crustal structure of the slab and the subduction zone more in general (Fig. 4). The first transect, acquired during the TICOSECT and COTCOR projects, crossed the entire southern Costa Rica across the Talamanca Cordillera and ended in the Limon Basin on the Caribbean coast (Stavenhagen et al. 1998) imaging the subducting Cocos

Ridge to a depth of about 30 km below the margin (Fig. 4). The TICOSECT transect revealed that the Cocos Ridge thickened the oceanic crust to ~15 km thick. A second transect traversed through northern Costa Rica across the Nicoya Peninsula and the active volcanic arc reaching the Nicaraguan border (Sallares et al. 2001) (Fig. 4). This transect imaged the subducting Cocos plate to a depth of 40 km beneath the Nicoya Peninsula. The most recent experiment, the TICO-CAVA transect, is located in central Costa Rica intersecting the CAVA between Barva and Irazu volcanoes (Fig. 4). TICO-CAVA is an onshore experiment designed to investigate the formation of juvenile crust (Hayes et al. 2013). The experiment suggested that the crustal thickness beneath the volcanic front in Costa Rica is ~40 km (Fig. 3). The

average lower-crustal velocities, between 6.8 and 7.1 km/s, appear to be lower than modern island arc velocities, suggesting that felsic continental crust has been created at the volcanic arc in Central Costa Rica (Hayes et al. 2013).

3 The Caribbean Plate

3.1 The Forearc

Incoming plate subduction in Costa Rica has induced significant tectonic erosion, i.e. the removal of material from the base of the upper plate (Ranero and von Huene 2000; Vannucchi et al. 2001, 2003). Here, tectonic erosion occurs at different scales, and it has been detected by several investigation techniques.

Incoming seamounts left characteristic margin-perpendicular indentations and grooves on the trench and outer slope with a net subsidence record within the wake of subducted seamounts (von Huene et al. 1995, 2000) (Fig. 2). Reflection seismics showed fault-bounded mega-lenses present along the plate boundary which have been interpreted to be portions of the upper plate detached from its base (Ranero and von Huene 2000). A third independent dataset has been acquired through ocean drilling, ODP Leg 170, IODP Exp. 334 and 344 (Fig. 4). This uses the occurrence of subaerial deposits buried by deepening-upward sedimentary sequences as a recorder of the late Tertiary subsidence of the outer fore arc (Vannucchi et al. 2001, 2003, 2013). The Costa Rica forearc NW of Osa peninsula is an area where the sedimentation rates are very high reaching 1,200 m/m.y. while the adjacent trench axis remains sediment starved (Vannucchi et al. 2013).

The inner fore arc along the Costa Rican margin records a history of net uplift (Gardner et al. 1992, 2001, 2013; Fisher et al. 1998; Sak et al. 2009; Morell et al. 2012). This is in strong contrast to the net subsidence in the outer fore arc. The inner fore arc is dissected by a system of active near-vertical faults oriented at high angles to the margin (Fig. 4). These faults segment the forearc thrust belt into blocks with strongly

variable uplift rates (Fisher et al. 1998; Marshall et al. 2000; Sak et al. 2009). The rivers draining this section of the Pacific slope typically follow these margin-perpendicular faults. Interestingly, the pattern of spatially variable fore arc uplift revealed by the correlation of marine and fluvial terraces along the Costa Rican Pacific coast is also spatially linked to the distribution of incoming seamounts. Uplift rates range from 1 to 8 mm/yr. The most rapid uplift occurs inboard of the Cocos Ridge within the Fila Costeña fold-and-thrust belt (Gardner et al. 1992, 2001, 2013; Fisher et al. 1998; Sak et al. 2009; Morell et al. 2012) (Fig. 4).

3.2 The Arc

In Costa Rica the CAVA is traditionally divided into two cordilleras or mountains ranges (Fig. 4): The Cordillera Volcánica de Guanacaste (CVG) and the Cordillera Volcánica Central (CVC). The Quaternary volcanoes of the CVG are from NW to SE, (see Figs. 1 and 3): Orosí-Cacao, Rincón de la Vieja, Miravalles, Tenorio-Montezuma and Chato-Arenal. Orosí-Cacao, Rincón de la Vieja, Miravalles, and Tenorio-Montezuma are shield-like stratovolcanoes build by coalescing lava flows and pyroclastic material emitted from multiple vents. While to the north, the low-relief landscape enhances the sharp morphology of the volcanoes, to the south the CVG lies behind the eroded massif of the extinct Tilarán Cordillera, masking the most active, but relatively small (15 km³) Arenal volcano. The Volcanoes of the CVG have geochemical signatures that are transitional between the depleted mantled source and high subduction signal of the Nicaragua volcanoes and the enriched mantle source and low subduction signal of the central Costa Rica volcanoes (Herrstrom et al. 1995; Carr et al. 2003).

The CVC extends for approximately 80 km in central Costa Rica and consists of the Platanar-Provenir, Póas, Barva, Irazú and Turrialba volcanoes. Turrialba Volcano is offset 10 km northwards with respect to the other volcanoes of the Cordillera Central. These are

composite shield volcanoes located northeast of the extinct Aguacate Cordillera. With peak elevations ranging from 2,000 to 3,400 m, these massive, broad-shouldered volcanoes are the largest volcanoes, in both area and volume, of the entire CAVA. Their summits exhibit wide calderas with multiple craters and transverse alignments of parasitic cones. The geochemical signal of the CVC is that of ocean-island basalt (Herrstrom et al. 1995; Carr et al. 2003).

In south-eastern Costa Rica in the Cordillera del Talamanca (Fig. 4) active arc-volcanism stopped at 5 Ma at the earliest, although 1–4 Ma pyroclastic flows (De Boer et al. 1995) and Pliocene— \approx 1.5 Ma—adakites are widespread, but volumetrically limited (Gans et al. 2002; Goss et al. 2004; MacMillan et al. 2004). These mountains extend to almost 4000 m in elevation and they were glaciated during the Pleistocene (Protti 1996; Lachniet 2004). The Cordillera de Talamanca is composed of a suite of Neogene-Quaternary intrusive (principally granodiorites) and extrusive rocks (andesites) (De Boer et al. 1995; Alvarado 2000; MacMillan et al. 2004).

The large lateral variations in relief and geochemistry of the CAVA in Costa Rica appear to be directly related to strong lateral changes in the nature of the subducting Cocos plate (Fig. 2). The overriding Caribbean plate, in fact, does not appear to play a strong role in controlling or contaminating the volcanic products of the arc (Plank et al. 2002; Patino et al. 2000). Although the eastern margin of the Caribbean plate has a long history of subduction starting in the Late Jurassic, the on-land record of the CAVA in Costa Rica is well recorded starting from the Miocene.

3.3 The Costa Rican Basement

The Caribbean plate is formed by the combination of two main lithospheric elements (Fig. 4): the Precambrian-Mesozoic continental *Chortis block* to the north-west and the Cretaceous oceanic plateau *Caribbean Large Igneous Province*—*CLIP*—, also called *Chorotega block* to

the south-west. The SW-NE contact between these two elements runs parallel to the Nicaragua-Costa Rica political boundary. The Chortis block is the byproduct of a long tectonic evolution with a nucleus of Paleozoic and Grenville-age metamorphic basement surrounded by Jurassic-Cretaceous ophiolitic complexes exposed along suture zones (Giunta and Orioli 2011) and late Cretaceous collided arc rocks (Rogers et al. 2007). The origin, tectonic significance and interaction of the Chortis and CLIP elements are still controversial—for example there is an ongoing argument regarding the allochthonous versus in situ origin of the Caribbean Plate (Pindell 1994; Meschede and Frisch 1998; Gahagan et al. 2007; Rogers et al. 2007; Giunta and Oliveri 2009; James 2009). According to the allochthonous hypothesis, the CLIP is the product of a Late Cretaceous period of vigorous submarine volcanism (Sinton et al. 1998) associated with the onset of the Galápagos mantle plume activity (or possibly the initiation of a new spreading center above a preexisting plume during the Late Cretaceous evolution of South American-African rifting). The emplacement of CLIP between the North and South America plates would then be the effect of its eastward migration, due to the subduction of the Farallon plate beneath the Caribbean plate, which commenced along the MAT in the Late Cretaceous (72–65 Ma) (Pindell 1994; Hoernle et al. 2004).

Subsequent dating, however, has extended the duration of CLIP volcanism to 70 m.y. (69–139 Ma) with the main volcanic events at \sim 95–72 Ma (Hoernle et al. 2004), which makes this period far too long for the igneous province to be formed by a single plume head or plume-centered spreading center initiation event. Hoernle et al. (2004) propose that CLIP is the result of several oceanic intraplate igneous structures that were aggregated through subduction process with Galapagos hotspot being the main, but not sole factor responsible for CLIP formation. The Galapagos hot spot also formed younger ocean islands and aseismic ridge terrains now accreted to the eastern margin of the Caribbean Plate such as the 60 Ma Quepos and the



25 Ma Osa terrains (Hauff et al. 1997, 2000; Vannucchi et al. 2006).

The lithospheric structure of the Caribbean plate is directly linked to the characteristics of these two elements, but also to the great variety of the plate boundary interactions including subduction (west coast of Central America, Puerto Rico and Lesser Antilles), transform faults (Motagua-Chelungpu and Venezuela), sea-floor spreading (Cayman Trough), and continental collision (Colombian Cordilleras). Northern Costa Rica is shaped according to the classic subduction margin profile with a deep trench ($\approx 5,000$ m), an active Wadati-Benioff zone and a volcanic arc while Southern Costa Rica has a shallower ($\approx 2,000$ m) trench, a shallower Wadati-Benioff zone and an extinct volcanic arc related to the subduction of the Cocos Ridge.

4 Summary and Ongoing Questions

As is often typical in Earth Sciences, learning more about the timing of the Geological and Geodynamical evolution of Costa Rica has led to new questions regarding its formation and evolution. The origin of Costa Rican arc basement is still uncertain, although clearly linked in part to the origin of the Caribbean Large Igneous Province. The cessation of major arc-like volcanism along the Cordillera de Talamanca, the highest mountains along the Central American Volcanic Arc, does not appear to be directly linked to the underthrusting of the Cocos Ridge because Ridge material does not lie beneath the Cordillera de Talamanca proper, and its subduction into the Costa Rican trench occurred well after the cessation of Talamanca arc volcanism. The Panama-Nazca-Plate margin does not record simple subduction as in Costa Rica, and the ongoing westward migration of the (Cocos-Nazca) Panama Transform Fault will lead to further short-term changes in the evolution of the southern Costa Rican margin. The Costa Rican margin is already recognized as the ‘type-example’ for a terrestrial end-member in how subduction erosion can modify a subduction margin. We suspect that the evolution of the

Cordillera de Talamanca may provide another ‘type example’ for how subduction processes shape the evolution of arc crust—after we can better understand what actually happened at a crustal and mantle level during this extreme event. It is even possible that this evolution is strongly linked to the recent formation of the Panama Land Bridge that has had profound effects on its surrounding marine and continental biomes.

References

- Abratis M, Worner G (2001) Ridge collision, slab-window formation, and the flux of Pacific asthenosphere into the Caribbean realm. *Geology* 29:127–130
- Adamek S, Tajima F, Wiens DA (1987) Seismic rupture associated with subduction of the Cocos Ridge. *Tectonics* 6:757–774
- Alvarado GE (2000) Los volcanes de Costa Rica: Geología, historia, y riqueza natural. San José, Costa Rica, Editorial de la Universidad Nacional Estatal a Distancia (in Spanish)
- Arroyo IG, Alvarado GE, Flueh ER (2003) Local seismicity at the Cocos Ridge-Osa Peninsula Subduction Zone, Costa Rica. In: Proceedings AGU fall meeting San Francisco, 2003, p Abstract S52F-0174
- Arroyo IG, Husen S, Flueh ER, Gossler J, Kissling E, Alvarado GE (2009) Three-dimensional P-wave velocity structure on the shallow part of the Central Costa Rican Pacific margin from local earthquake tomography using off- and onshore networks. *Geophys J Int* 179:827–849
- Arroyo IG, Grevenmeyer I, Ranero CR, von Huene R (2014) Interplate seismicity at the CRISP drilling site: the 2002 Mw 6.4 Osa Earthquake at the southeastern end of the Middle America Trench. *Geochem Geophys Geosyst* 15:3035–3050
- Barckhausen U, Roeser HA, von Huene R (1998) Magnetic signature of upper plate structures and subducting seamounts at the convergent margin off Costa Rica. *J Geophys Res* 103:7079–7093
- Barckhausen U, Ranero CR, von Huene R, Cande SC, Roeser HA (2001) Revised tectonic boundaries in the Cocos Plate off Costa Rica: implications for the segmentation of the convergent margin and for plate tectonic models. *J Geophys Res* 106:19207–19220
- Bilek SL, Lithgow-Bertelloni C (2005) Stress changes in the Costa Rica subduction zone due to the 1999 $M_w = 6.9$ Quepos earthquake. *Earth Planet Sci Lett* 230:97–112
- Bilek SL, Schwartz SY, DeShon HR (2003) Control of seafloor roughness on earthquake rupture behavior. *Geology* 31:455–458

- Carr MJ, Feigenson MD, Patino LC, Walker JA (2003) Volcanism and Geochemistry in Central America: progress and problems, vol 138. Inside the Subduction Factory, Geophysical Monograph-American Geophysical Union, pp 153–179
- Collins LS, Coates AG, Jackson JBC, Obando JA (1995) Timing and rates of emergence of the Limón and Bocas del Toro basins: Caribbean effects of Cocos Ridge subduction? *Geol Soc Am, Spec Pap* 295:263–290
- De Boer JZ, Drummond MS, Bordelon MJ, Defant MJ, Bellon H, Mauri RC (1995) Cenozoic magmatic phases of the Costa Rican island arc (Cordillera de Talamanca). In: Mann P (ed) *Geologic and tectonic development of the Caribbean plate boundary in Southern Central America*, vol 295, pp 35–55
- DeMets C (2001) A new estimate for present-day Cocos-Caribbean plate motion: implications for slip along the Central American volcanic arc. *Geophys Res Lett* 28:4043–4046
- DeMets C, Gordon RG, Argus DF, Stein S (1990) Current plate motions. *Geophys J Int* 101:425–478
- Dinc AN, Koulakov I, Thorwart MM, Rabbel W, Flueh ER, Arroyo IG, Taylor W, Alvarado G (2010) Local earthquake tomography of central Costa Rica: transition from seamount to ridge subduction. *Geophys J Int* 183:286–302
- Dzierma Y, Rabbel W, Thorwart MM, Flueh ER, Mora MM, Alvarado GE (2011) The steeply subducting edge of the Cocos Ridge: evidence from receiver functions beneath the northern Talamanca Range, south-central Costa Rica. *Geochem Geophys Geosyst* 12. <https://doi.org/10.1029/2010gc003477>
- Fisher DM, Gardner TW, Marshall JS, Sak PB, Protti M (1998) Effect of subducting sea-floor roughness on fore-arc kinematics Pacific coast, Costa Rica. *Geology* 26:467–470
- Fisher DM, Gardner TW, Sak PB, Sanchez JD, Murphy K, Vannucchi P (2004) Active thrusting in the inner forearc of an erosive convergent margin, Pacific coast, Costa Rica. *Tectonics* 23. <https://doi.org/10.1029/2002tc001464>
- Gahagan L, Rogers DE, Mann P (2007) Chapter 8. Overview of plate tectonic history and its unresolved tectonic problems. In: Bundschuh J, Alvarado GE (eds) *Central America: geology, resources and hazards*. Taylor & Francis, London, pp 205–241
- Gans PB, Macmillan I, Alvarado-Induni G, Perez W, Sigaran C (2002) Neogene evolution of the Costa Rican arc. *Geol Soc Am 2002 Annual meeting* 34:6, Denver Annual Meeting, October 27–30, 2002
- Gardner TW, Verdonck D, Pinter NM, Slingerland R, Furlong KP, Bullard TF, Wells SG (1992) Quaternary uplift astride the aseismic Cocos ridge, Pacific coast, Costa-Rica. *Geol Soc Am Bull* 104:219–232
- Gardner T, Marshall J, Merritts D, Bee B, Burgette R, Burton E, Cooke J, Kehrwald N, Protti M, Fisher MD, Sak P (2001) Holocene forearc block rotation in response to seamount subduction, southeastern Peninsula de Nicoya, Costa Rica. *Geology* 29:151–154
- Gardner T, Fisher DM, Morell K, Cupper M (2013) Upper plate deformation in response to flat slab subduction inboard of the aseismic Cocos Ridge, Osa Peninsula, Costa Rica. *Lithosphere* 5:247–264
- Giunta G, Oliveri E (2009) Some remarks on the Caribbean Plate kinematics: facts and remaining problems. In: James KH, Lorente MA, Pindell JL (eds) *The origin and evolution of the Caribbean plate*, vol 328. *Geol Soc London*, pp 57–75
- Giunta G, Orioli S (2011) The Caribbean plate evolution: trying to resolve a very complicated tectonic puzzle. In: Sharkov EV (ed) *New frontiers in tectonic research—general problems, sedimentary basins and Island Arcs*. InTech, pp 221–248
- Goss A, Kay S, Mpodozis C (2004) Transient “adakites” and the role of forearc subduction erosion: examples from the Central Andean and Central American margins. In: *Proceedings 32nd IGC, Florence, Italy, 2004, Part 2*, p 1333
- Grafe K, Frisch W, Villa IM, Meschede M (2002) Geodynamic evolution of southern Costa Rica related to low-angle subduction of the Cocos Ridge: constraints from thermochronology. *Tectonophysics* 348:187–204
- Hauff F, Hoernle K, Schmincke HU, Werner R (1997) A Mid Cretaceous origin for the Galapagos hotspot: volcanological, petrological and geochemical evidence from Costa Rican oceanic crustal segments. *Geol Rundsch* 86:141–155
- Hauff F, Hoernle K, Tilton G, Graham DW, Kerr AC (2000) Large volume recycling of oceanic lithosphere over short time scales: geochemical constraints from the Caribbean Large Igneous Province. *Earth Planet Sci Lett* 174:247–263
- Hayes JL, Holbrook WS, Lizarralde D, van Aven-donk HJA, Bullock AD, Mora M, Ramirez C, Harder S, Alvarado GE (2013) Crustal structure across the Costa Rican Volcanic Arc. *Geochem Geophys Geosyst* 14:1087–1103
- Herrstrom E, Reagan M, Morris J (1995) Variations in lava composition associated with flows of asthenosphere beneath southern Central America. *Geology* 23:617–620
- Hey R (1977) Tectonic evolution of the Cocos-Nazca spreading center. *Geol Soc Am Bull* 88:1404–1420
- Hoernle K, Hauff F, van den Bogaard P (2004) 70 m.y. history (139–69 Ma) for the Caribbean large igneous province. *Geology* 32:697–700
- Husen S, Kissling E, Quintero R (2002) Tomographic evidence for a subducted seamount beneath the Gulf of Nicoya, Costa Rica. The cause of the 1990 Mw = 7.0 Gulf of Nicoya earthquake. *Geophys Res Lett* 29(8). <https://doi.org/10.1029/2001gl014045>
- Husen S, Quintero R, Kissling E, Hacker B (2003) Subduction-zone structure and magmatic processes beneath Costa Rica constrained by local earthquake tomography and petrological modelling. *Geophys J Int* 155:11–32
- James KH (2009) In-situ origin of the Caribbean: discussion of data. In: James KH, Lorente, MA,



- Pindell JL (eds) The origin and evolution of the Caribbean plate, vol 328. Geol Soc London, pp 77–126
- Kolarsky RA, Mann P, Montero W (1995) Island arc response to shallow subduction of the Cocos Ridge, Costa Rica. In: Mann P (ed) Geologic and tectonic development of the Caribbean plate boundary in Southern Central America, vol 295, pp 235–262
- Lachniet MS (2004) Quaternary glaciation in Guatemala and Costa Rica. In: Ehlers J, Gibbard PL (eds) Quaternary glaciations—extent and chronology. Part III: South America, Asia, Africa, Australia, Antarctica, 2c, pp 135–138
- LaFemina P, Dixon TH, Govers R, Norabuena E, Turner H, Saballos A, Mattioli G, Protti M, Strauch W (2009) Fore-arc motion and Cocos Ridge collision in Central America. *Geochem Geophys Geosyst* 10:Q05S14. <https://doi.org/10.1029/2008gc002181>
- Lonsdale P (2005) Creation of the Cocos and Nazca plates by fission of the Farallon plate. *Tectonophysics* 404:237–264
- Lonsdale P, Klitgord KD (1978) Structure and tectonic history of the eastern Panama Basin. *Geol Soc Am Bull* 89:981–999
- MacMillan I, Gans PB, Alvarado G (2004) Middle Miocene to present plate tectonic history of the southern Central American Volcanic Arc. *Tectonophysics* 392:325–348
- Marshall JS, Fisher DM, Gardner TW (2000) Central Costa Rica deformed belt: kinematics of diffuse faulting across the western Panama block. *Tectonics* 19:468–492
- Meschede M, Frisch W (1998) A plate tectonic model for the Mesozoic and Early Cenozoic history of the Caribbean Plate. *Tectonophysics* 296:269–291
- Morell KD, Fisher DM, Gardner TW (2008) Inner forearc response to subduction of the Panama Fracture Zone, southern Central America. *Earth Planet Sci Lett* 265:82–95
- Morell KD, Kirby E, Fisher DM, van Soest M (2012) Geomorphic and exhumational response of the Central American Volcanic Arc to Cocos Ridge subduction. *J Geophys Res* 117:B04409. <https://doi.org/10.1029/2011JB008969>
- Morgan JW (1978) Rodriguez, Darwin, Amsterdam, ..., a second type of hotspot Island. *J Geophys Res* 83:5355–5360
- Norabuena E, Dixon TH, Schwartz S, DeShon H, Newman A, Protti M, Gonzalez V, Dorman L, Flueh ER, Lundgren P, Pollitz F, Sampson D (2004) Geodetic and seismic constraints on some seismogenic zone processes in Costa Rica. *J Geophys Res* 109(B11): B11403. <https://doi.org/10.1029/2003JB002931>
- Pindell JL (1994) Evolution of the Gulf of Mexico and the Caribbean. In: Donovan SK, Jackson TA (eds) Caribbean geology: an introduction. University of the West Indies Publishers Association/University of the West Indies Press, Kingston, Jamaica, pp 13–39
- Protti R (1996) Evidencias de glaciación en el Valle del General (Costa Rica) durante el Pleistoceno tardío. *Rev Geol Am Central* 19(20):75–85
- Protti M, Guendel F, McNelly 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: Mann P (ed) Geologic and tectonic development of the Caribbean plate boundary in Southern Central America, vol 295, pp 309–343
- Protti M, Guendel F, Malavassi E (2001) Evaluación del potencial sísmico de la Península de Nicoya, Heredia, Costa Rica. Editorial Fundación Universidad Nacional
- Ranero CR, von Huene R (2000) Subduction erosion along the Middle America convergent margin. *Nature* 404:748–752
- Ranero CR, Weinrebe W, Grevemeyer I, von Huene R, Reichert C (2004) The relation between tectonics, fluid flow and seismogenesis at convergent erosional margins. *EOS (Trans) American Geophysical Union*, vol 85, no 47, Fall Meeting Suppl, p S43D-01
- Rogers RD, Mann P, Emmet PA (2007) Tectonic terranes of the Chortis block based on integration of regional aeromagnetic and geologic data. *Geol Soc Am, Spec Pap* 428:65–88
- Ryan WBF, Carbotte SM, Coplan JO, O'Hara S, Melkonian A, Arko R, Weissel RA, Ferrini V, Goodwillie A, Nitsche F, Bonczkowski J, Zensky R (2009) Global multiresolution topography synthesis. *Geochem Geophys Geosyst* 10:Q03014. <https://doi.org/10.1029/2008GC002332>
- Sak PB, Fisher DM, Gardner TW, Marshall JS, LaFemina PC (2009) Rough crust subduction, forearc kinematics, and Quaternary uplift rates, Costa Rican segment of the Middle American Trench. *Geol Soc Am Bull* 121:992–1012
- Sinton CW, Duncan RA, Storey M, Lewis J, Estrada JJ (1998) An oceanic flood basalt province within the Caribbean plate. *Earth Planet Sci Lett* 155:221–235
- Sitchler JC, Fisher DM, Gardner TW, Protti M (2007) Constraints on inner forearc deformation from balanced cross sections, Fila Costena thrust belt, Costa Rica. *Tectonics* 26:TC6012. <https://doi.org/10.1029/2006tc001949>
- Stavnenhagen AU, Flueh ER, Ranero CR, McIntosh KD, Shipley T, Leandro G, Schulze A, Dañobeitia JJ (1998) Seismic wide-angle investigations in Costa Rica—a crustal velocity model from the Pacific to the Caribbean. *Zbl Geol Paläontol* 1:393–408
- Syracuse EM, Abers GA, Fischer K, MacKenzie L, Rychert C, Protti M, Gonzalez V, Strauch W (2008) Seismic tomography and earthquake locations in the Nicaraguan and Costa Rican upper mantle. *Geochem Geophys Geosyst* 9:Q07S08. <https://doi.org/10.1029/2008gc001963>
- Tajima F, Kikuchi M (1995) Tectonic implications of the seismic ruptures associated with the 1983 and 1991 Costa Rica earthquakes. In: Mann P (ed) Geological and tectonic development of the Caribbean plate boundary in Southern Central America. *Geol Soc Am, Spec Pap* 295:327–340

- 827 Vannucchi P, Scholl DW, Meschede M, McDougall-Reid K (2001) Tectonic erosion and consequent collapse of
828 the Pacific margin of Costa Rica: combined implica-
829 tions from ODP Leg 170, seismic offshore data, and
830 regional geology of the Nicoya Peninsula. *Tectonics*
831 20:649–668
832
- 833 Vannucchi P, Ranero CR, Galeotti S, Straub SM,
834 Scholl DW, McDougall-Ried K (2003) Fast rates of
835 subduction erosion along the Costa Rica Pacific
836 margin: Implications for nonsteady rates of crustal
837 recycling at subduction zones. *J Geophys Res* 108
838 (B11):2511. <https://doi.org/10.1029/2002JB002207>
839
- 840 Vannucchi P, Fisher DM, Gardner TW, Bier S (2006)
841 From seamount accretion to tectonic erosion: forma-
842 tion of Osa Mélangé and the effects of Cocos Ridge
843 subduction in southern Costa Rica. *Tectonics* 25:
844 TC2004. <https://doi.org/10.1029/2005tc001855>
845
- 846 Vannucchi P, Sak PB, Morgan JP, Ohkushi K, Ujiie K,
847 Scientists IES (2013) Rapid pulses of uplift, subsi-
848 dence, and subduction erosion offshore Central Amer-
849 ica: implications for building the rock record of
850 convergent margins. *Geology* 41:995–998
- 851 Vergara Muñoz A (1988) Tectonic patterns of the Panama
852 Block deduced from seismicity, gravitational data and
853 earthquake mechanisms: implications to the seismic
854 hazard. *Tectonophysics* 154:253–267
855
- 856 von Huene R, Bialas J, Flueh E, Cropp B, Csernok T,
857 Fabel E, Hoffmann J, Emeis K, Holler P, Jeschke G,
858 Leandro MC, Perez Fernandez I, Chavarria SJ,
859 Florez HA, Escobedo ZD, Leon R, Barrios LO
860 (1995) Morphotectonics of the Pacific convergent
861 margin of Costa Rica. In: Mann P (ed) *Geologic and
862 tectonic development of the Caribbean Plate boundary
863 in southern Central America*. *Geol Soc Am, Spec Pap*
864 295:291–307
865
- 866 von Huene R, Ranero CR, Weinrebe W, Hinz K (2000)
867 Quaternary convergent margin tectonics of Costa
868 Rica, segmentation of the Cocos Plate, and Central
869 American volcanism. *Tectonics* 19:314–334
870
- 871 Walther CHE (2003) The crustal structure of the Cocos
872 ridge off Costa Rica. *J Geophys Res* 108(B3), p. art.
873 no. 2136. <https://doi.org/10.1029/2001jb000888>
874
- 875
- 876 Werner R, Hoernle K, van den Bogaard P, Ranero CR,
877 von Huene R (1999) Drowned 14-m.y.-old Galapagos
878 archipelago off the coast of Costa Rica: implications
879 for tectonic and evolutionary models. *Geology*
880 27:499–502