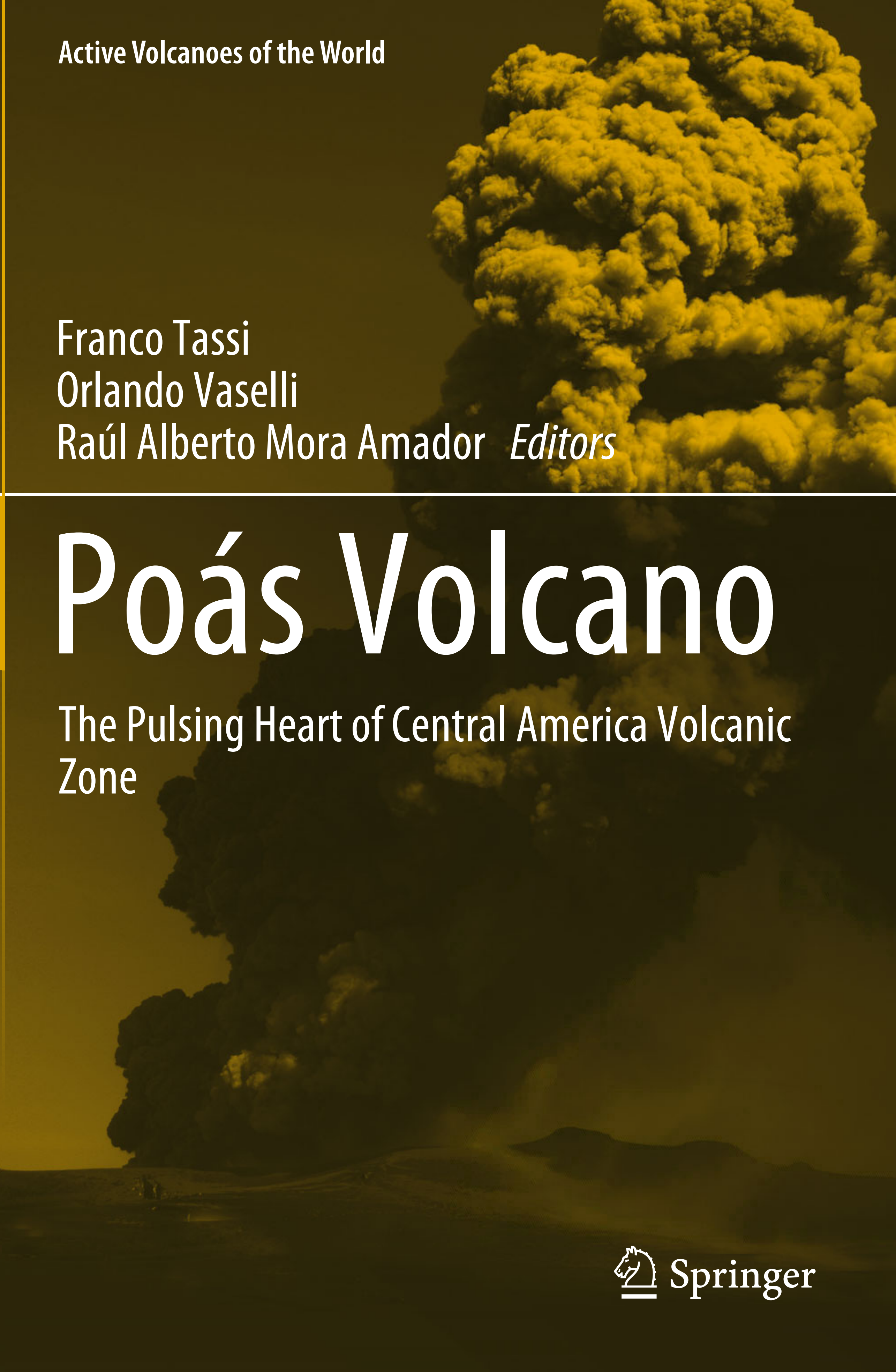
Active Volcanoes of the World

Franco Tassi
Orlando Vaselli
Raúl Alberto Mora Amador *Editors*

Poás Volcano

The Pulsing Heart of Central America Volcanic Zone



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Active Volcanoes of the World

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About 500 active volcanoes presently exist on the Earth's surface, of which around 50 erupt each year. Volcanoes played a crucial role in the evolution of the planet and early life, and are constantly reshaping the morphology of Planet Earth. Many active volcanoes are located in dense settlement areas, with over 500 million people living in close proximity of still active or dormant volcanoes.

On one side, volcanoes provide valuable soil and rock basis for agriculture, but often the "mountains of fire" cause disastrous societal and economical disasters caused by ash clouds, lahars, lava flows, and pyroclastic flows. Eruptions are still difficult to predict, although volcanologists around the world are constantly working on new ways to understand the character and behavior of volcanoes.

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ISSN 2195-3589 ISSN 2195-7029 (electronic)
Active Volcanoes of the World
ISBN 978-3-319-02155-3 ISBN 978-3-319-02156-0 (eBook)
https://doi.org/10.1007/978-3-319-02156-0

Library of Congress Control Number: 2019930645

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Foreword

The April 2017 strong phreatomagmatic eruption of Poás dramatically changed the morphology of the active crater and temporarily stopped the usual crowd of tourists. A year later at the end of August 2018, the National Park at the Poás crater partially re-opened to the public.

Poás volcano represents an excellent site for common people worldwide to be a bit educated about "*how our Earth works*". A perfect shape of the crater, a steaming crater lake, roaring fumaroles, smell of sulphur, beautiful outcrops of volcanic sequences and intense hydrothermal alteration are just a few examples of what this volcano can offer to tourists and scientists. The observations of these geological attractions are facilitated by a comfortable way to get to the rim of the crater. It is likely that the good accessibility to the Poás volcano crater has allowed to become this site one of the most studied areas for volcanologists working on the origin and dynamics of a powerful, very active, volcano–hydrothermal system. This is a natural laboratory where in situ one can observe how Nature performs experiments on the magmatic fluid–water–rock interaction; and not only to observe but also by some way to participate by performing sampling and analyses of the products of this interaction. The "Laguna Caliente"—the Poás´ crater lake—decades ago became one of the first sites where volcanologists started to study and model the heat and mass balance of an active crater lake and made detailed and precise studies of the maximum of possible isotopic, elemental and molecular geochemical systems.

The Poás crater has been the object of many international field workshops and fieldworks for generations of specialists in Earth Sciences. This active and potentially dangerous volcano is monitored by specialists from both OVSICORI-UNA (the Volcanological and Seismological Observatory settled in Heredia) and University of Costa Rica in collaboration with many foreigner scientists. Such intensive scientific attention to the volcano has exponentially increased the knowledge about Poás, and new data are continuously produced. A very fast development of the modern analytical and field techniques requires regular "summing up", e.g. a scientific report about the latest results obtained by the scientific community related to Poás.

This book compiles a set of papers that covers a wide spectrum of topics—from a general modern view on the tectonics and geodynamics of the Costa Rican segment of the Central American Volcanic Arc to an historical essay about the place of Poás in the life of the Central American people.

A reader will find here approaches and data, which are generally interesting and important for many researchers and students in the Earth Sciences. Many thanks to the editors and authors for this excellent issue.

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Introduction

"… during the previous year's Miguel Alfaro himself had seen a vapour column, which also threw stones upwards, and around those sulphur accumulations and in the volcanic ash a blue flame burned. In the surroundings ash also found conical masses of pure sulphur, with an altitude of 3 to 4 feet. The lake then was a lot smaller; nevertheless, the water roared with more power and appeared more acidic and hotter than now. It seemed that at that time the volcano would have been a lot more active in throwing ash, and that it went gradually slowing down" (descriptions of Miguel Alfaro of 1828).

Von Frantzius (1861)

It was a privilege to edit this book on the Poás volcano (Costa Rica), which consists of 13 contributions about different aspects and approaches related to geodynamics, volcanology, seismology, fluid geochemistry, botany and zoology and legends related to one of the most active volcanoes in the world. In April 2017, when a new eruptive phase commenced, we started receiving the contributions by the authors and some of the chapters had to be modified to have as much as possible an update related to the renewal activity at Poás. This was one of the reasons why this book was a little bit delayed with respect to what was planned.

Poás is a complex strato-volcano, located in the Province of Alajuela, with an altitude of 2708 m a.s.l. and is part of the local national park. This volcano can be regarded as one of the most important touristic attractions of Costa Rica. The turquoise colour of the acidic lake (Laguna Caliente) and the intense fumarolic activity are likely the most photographed shots in the whole country.

The Poás summit is characterized by three volcanic cones: Von Frantzius, Botos and the active crater, the latter being the site where the latest eruptions occurred. The surrounding area hosted vigorous fumaroles, particularly close to a pyroclastic cone (often reported in the literature as a dome) formed in the early fifties. The fumarolic gas discharges are responsible for the absence of vegetation in several portions of the park due to the acidic gases emitted from the crater. The outlet temperatures of the fumaroles close to the pyroclastic

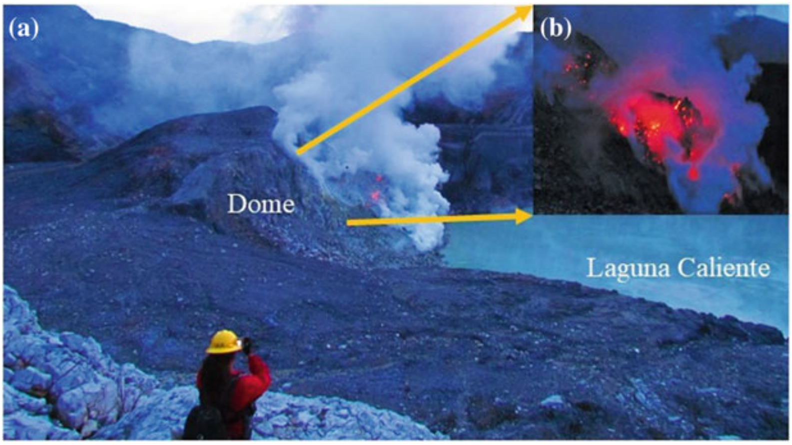

Fig. 1 High-temperature fumarole at the pyroclastic cone (often reported in the literature as a dome): **a** from July to September 2011 a temperature up to 900 °C was measured; **b** incandesce at the pyroclastic cone

cone (often reported in the literature as a dome), which was almost completely destroyed during an intense phreatomagmatic activity on the 22 April 2018, have shown dramatic changes from water boiling to magmatic (900 °C) temperatures, showing a spectacular incandescence (Fig. 1). Laguna Caliente is a hyper-acidic lake regarded as the most active crater lake in the world. The lake disappeared several times in the past: 1953, intermittent presence up to 1967, April 1989 and 1994, June 2017 and March 2018. Between March and August 2018, the lake was newly restored. Another peculiarity of Poás is associated with spectacular eruptions of sulphur (described since the nineteenth century), which are very rare in other volcanic areas worldwide. The typical eruptive activity at Poás is related to multiple phreatic eruptions (Fig. 2). In the eighties, the volcanologist F. D. Bennett suggested to call these events “erupciones Poasinas”, to be distinguished by other ordinary phreatic eruptions.

The National Park of Poás is one of the most visited parks in Central America and possibly of the whole Latin American countries. To date, more than 400,000 people are used to visit the crater from the beautiful mirador that offers a magnificent view of active crater and Laguna Caliente. Owing to the resumed volcanic activity in April 2017, the park was interdicted to all the tourists causing a severe economic loss. Fortunately, at the end of August 2018, the park newly opened to the public.

The final versions of the 13 chapters were submitted to Springer in early September 2018 that marked the second anniversary of the premature death of Bruno Capaccioni, an eminent scientist and volcanologist but, first of all, a friend. Bruno has worked with the editors and most of the authors of this

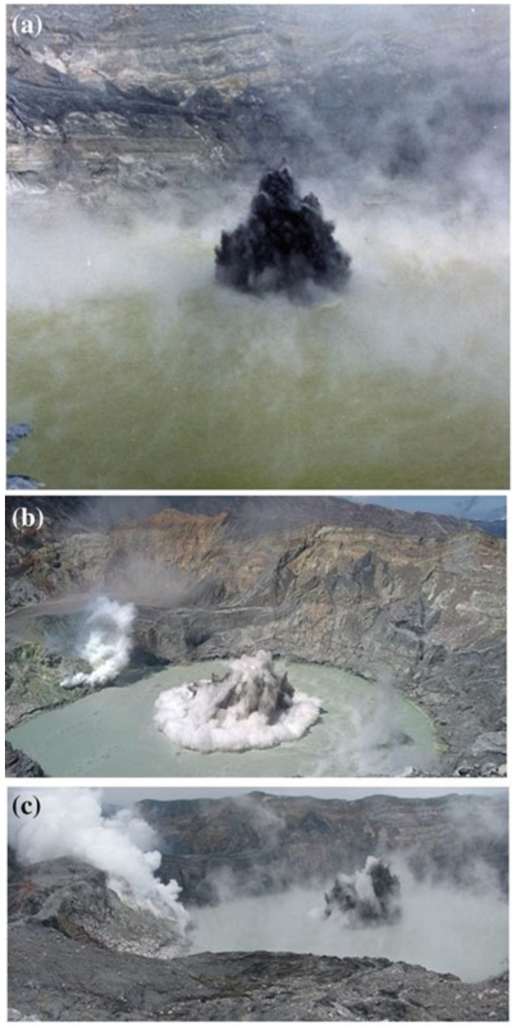

Fig. 2 Phreatic eruption: **a** Phreatic eruption occurred on 1988 (photograph by G. Soto); **b** phreatic eruption occurred on 1 May 2010 (photograph by A. B. Castro); **c** phreatic eruption occurred on 25 May 2011 (photograph by R. A. Mora Amador)

book at Poás that was one of his favourite volcanoes. His sympathy and his love for volcanoes will always remain with all those who were lucky to know him. We do wish to dedicate this book to his memory.

He will never be forgotten!

Overview of the Tectonics and Geodynamics of Costa Rica

Paola Vannucchi and Jason P. Morgan

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 ∼100 km^3/km/Ma beneath Nicoya Peninsula to 'extreme' short-duration peaks of ∼1,000 km^3/km/Ma beneath Osa Peninsula. The margin is currently both seismogenic and tsunamogenic, with seismicity in the Osa Peninsula nucleating along one of Earth's shallowest seismogenic plate interfaces. In Costa Rica, 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 ≈1,500 km—long Central America convergent margin. The Cocos plate subducts with a convergence direction N25°–N30°E with respect to the overriding Caribbean Plate at rates varying between 83 mm/yr in northern Costa Rica and 93 mm/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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F. Tassi et al. (eds.), *Poás Volcano*, Active Volcanoes of the World,
https://doi.org/10.1007/978-3-319-02156-0_1

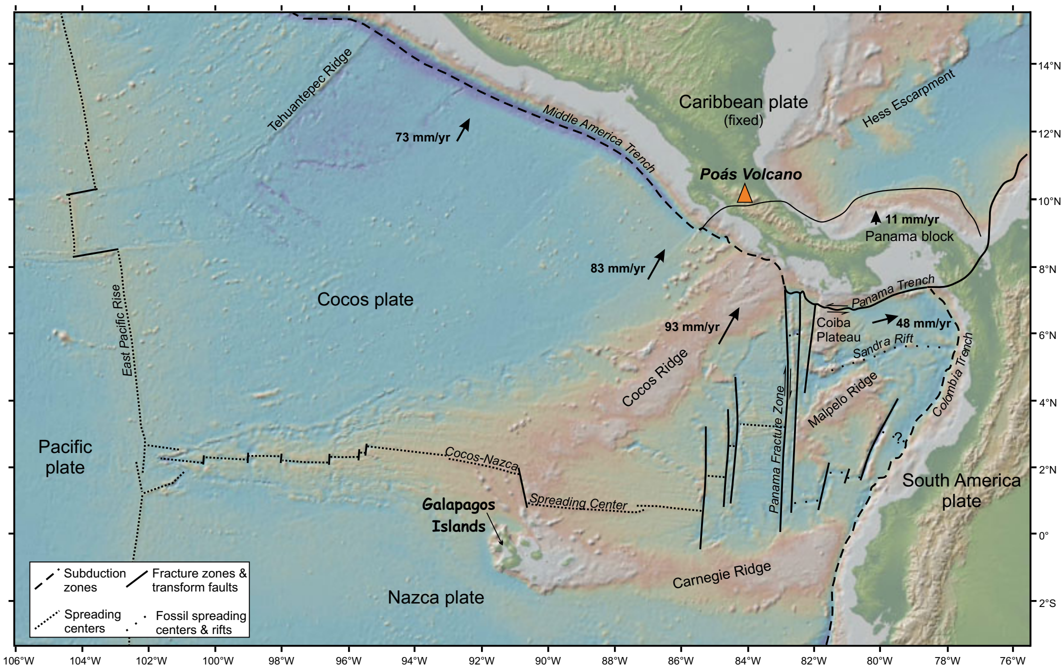

Fig. 1 Bathymetry, topography (http://www.geomapapp.org (Ryan et al. 2009)), and tectonic plate configuration in the region surrounding the Costa Rica. Arrows show plate motions with respect to the Caribbean plate (DeMets et al. 1990; DeMets 2001). Black dashed lines indicate trenches, black dotted lines 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 the arc 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

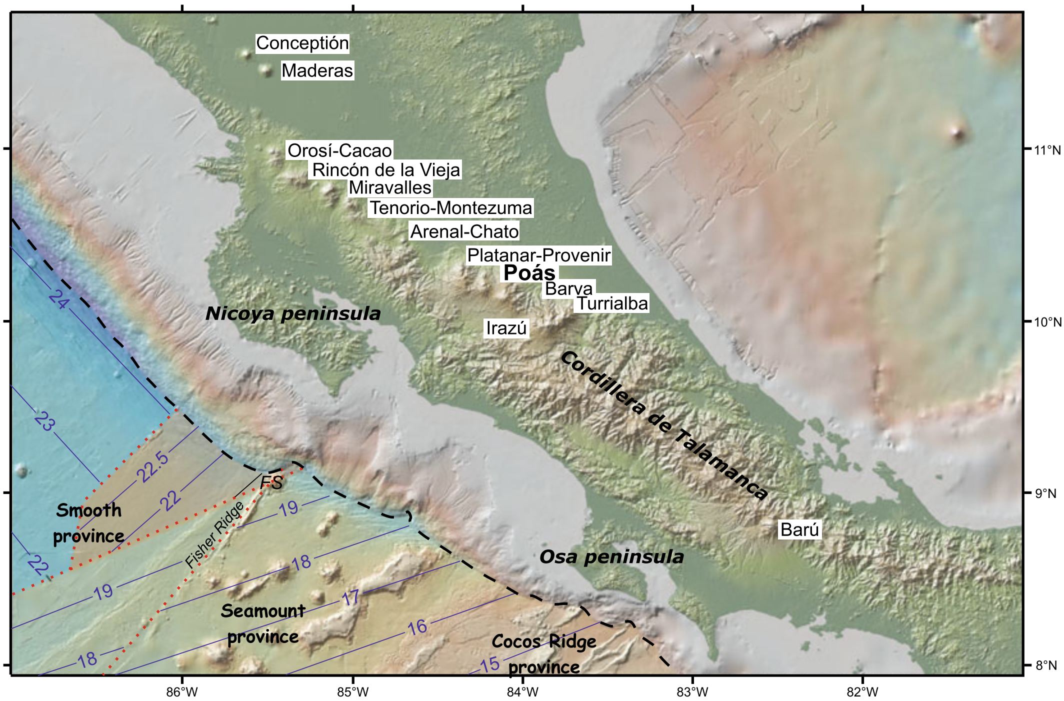

Fig. 2 Locations of volcanoes in Costa Rica and adjacent regions. Offshore Costa Rica shows a Cocos plate isochron map with ages derived from identification of seafloor spreading anomalies (Barckhausen et al. 2001). In blue is the crust generated at the East Pacific Rise, in red, orange and yellow the 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 ≈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 ~10° 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 (Ms = 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 (Ms = 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 (Kolarsky 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 batholits 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

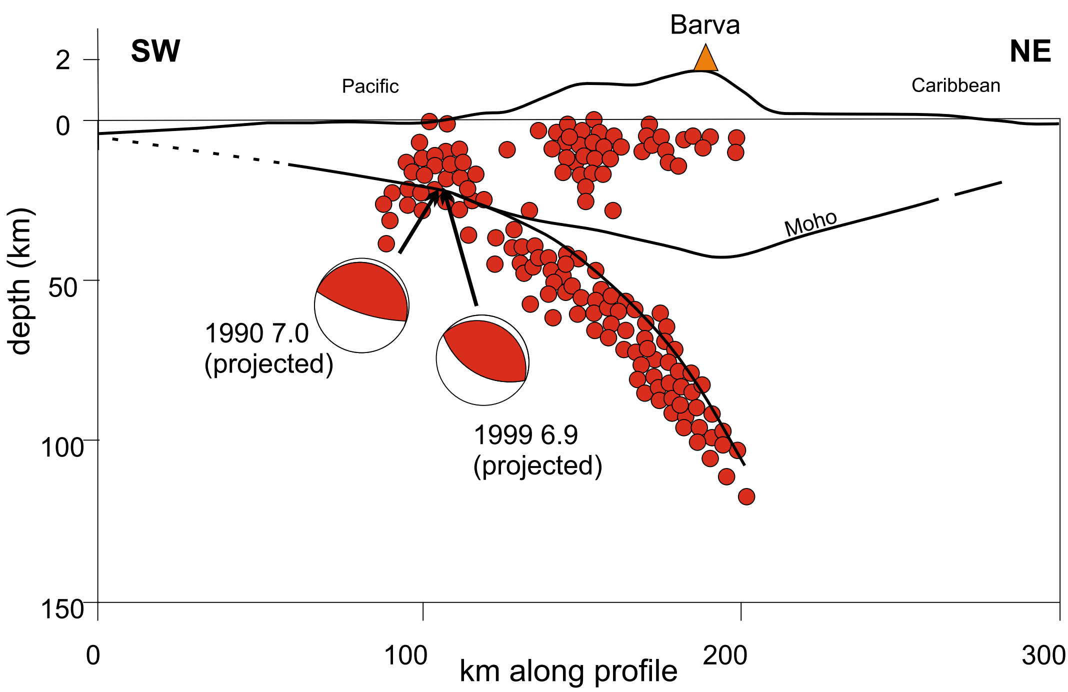

Fig. 3 Vertical section parallel to the dip of the subducting Cocos plate in the seamount-dominated segment off central Costa Rica. This section is coincident with the wide-angle seismic transect TICO-CAVA (Hayes et al. 2013—see Fig. 4 for location). The TICO-CAVA data constrain the crust and crust-mantle transition beneath the volcanic arc. Seismicity and slab depths are taken from Husen et al. (2003). Fault plain solutions of two large events within this area are also projected onto the section

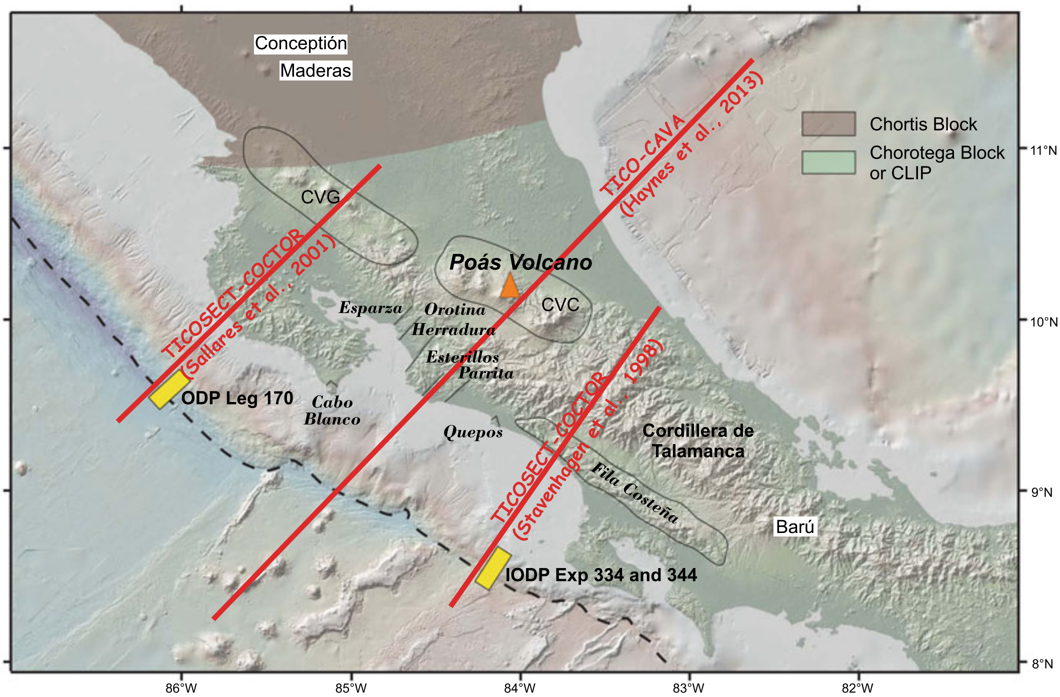

Fig. 4 Location of wide-angle seismic transects and ODP-IODP drilling expeditions discussed here. Named black line segments mark near-vertical faults perpendicular to the trench that dissect the margin in the central portion of the onshore forearc. To the south, where the Cocos Ridge subducts, the forearc 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 km^3) 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—≈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 ~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 (≈5,000 m), an active Wadati-Benioff zone and a volcanic arc while Southern Costa Rica has a shallower (≈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 Talamaca, 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.

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Geochemical and Geochronological Characterisation of the Poas Stratovolcano Stratigraphy

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Abstract

In this chapter the stratigraphy of Poás volcano by using geological, petrographical, geochronological and geochemical analyses on the volcanic products erupted during the last 600 ka is defined. The northern flank of Poás consists of the following Units and Members: Río Sarapiquí, La Paz, Puente de Mulas Member (possibly from another source, though interdigitated with Poás products), Río Cuarto Lavas, Von Frantzius, Congo, Bosque Alegre and Laguna Kopper. The products on the southern flank are the Colima Formation, La Paz, Tiribí, Achiote, Poasito, Sabana Redonda and Poás Lapilli Tuff. The central part of the volcano is made up of the Poás Summit Unit, which includes the Main and Botos craters. Rock composition varies from basalts to dacites. During the last 600 ka the content of K_2O and other oxides (e.g. TiO_2 and P_2O_5) and trace elements (e.g. Zr, Ba) has varied significantly through time, implying the presence of two geochemical end-members since the beginning of the magmatic activity at Poás: (1) the Sabana Redonda Geochemical Component ($TiO_2 > 1\%$) enriched in HSFE and other trace elements, present in La Paz Andesites, Lavas Río Cuarto, Poasito, Sabana Redonda, Poás Lapilli Tuff and Botos crater lavas and (2) The Von Frantzius Geochemical Component ($TiO_2 < 0.8\%$) that was recognized in the lavas from the Main Crater, Von Frantzius, Achiote, Bosque Alegre, Congo and Botos. Lavas related to both magmatic components have coexisted over time as indicated by those found at Botos and the Main Crater. Units possibly related to a common vent, i.e. La Paz, Achiote and Main

Electronic supplementary material **The online version of this chapter (https://doi.org/10.1007/978-3-319-02156-0_2) contains supplementary material, which is available to authorized users.**

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F. Tassi et al. (eds.), *Poás Volcano*, Active Volcanoes of the World,
https://doi.org/10.1007/978-3-319-02156-0_2

Crater, the percentages of K_2O and TiO_2 decreased through time.

Keywords
Poás volcano · Volcano stratigraphy · Volcano growth · Subduction zone

1 Introduction

Subduction processes recycle crustal material and sediments back into the mantle, directly influencing both the segregation of continental crust and the geochemical variability in the mantle (e.g. Plank and Langmuir 1993; Rudnick and Gao 2003; Hofmann 2003; Ryan and Chauvel 2014; Gazel et al. 2015). The Central American Volcanic front is characterized by drastic chemical variations, making it an ideal location to study the role of the subduction processes in the generation of juvenile continental crust and element recycling processes (Carr et al. 1990; Vogel et al. 2004; Saginor et al. 2011, 2013). In this chapter, we present the results related to one of the most active volcanoes of Costa Rica in the last decade: Poás, which can be regarded as the pulsing heart of Central America Volcanic Zone.

Poás volcano is a complex stratovolcano located in the southern end of the Central American Volcanic front (Vannucchi and Mason Chapter "Overview of the Tectonics and Geodynamics of Costa Rica"). It is one of the five active volcanoes of Costa Rica along with Rincon de la Vieja, Arenal, Turrialba, Irazu and belongs to the Central Volcanic Range (CVR). Located at Lat 10° 11′N and Lon 84° 13′W, it is just 30 km NW of the capital, San José, which, together with the other major cities of the Central Valley, hosts ~2.1 million inhabitants (Fig. 1). Due to its proximity to major cities, Poás volcano has a relevant scientific and sociological importance and in the past three decades several studies focused on the geology, geophysics and geochemistry of this apparatus. This has led to make considerable progress in understanding its historical eruptive cycles and present activity (e.g. Thorpe et al. 1981; Casertano et al. 1983; Prosser and Carr 1987; Cigolini et al. 1991; Rymer et al. 2000, 2009; de Moor et al. 2016; Mora Amador et al. Chapter "Volcanic Hazard Assessment of Poás (Costa Rica) Based on the 1834, 1910, 1953–1955 and 2017 Historical Eruptions"). In addition, other studies regarded the flanks of the volcano (e.g. Tournon 1984; Borgia et al. 1990; Soto 1999; Alvarado and Salani 2004; Gazel and Ruiz 2005; Carr et al. 2007; Montero et al. 2010; Alvarado et al. 2011). The work by Ruiz et al. (2010) was the first attempt to complete a geological map that studied the volcano as a whole edifice, from its flanks at ~400 m a.s.l. up to its summit at 2708 m a.s.l.

Here, new results of a comprehensive field mapping, geochemical analyses, Ar–Ar dating, high-resolution orthophotos and LiDAR data study of Poás volcano (Fig. 1) are presented. The main goal of this chapter was to understand the changes that this complex stratovolcano has experienced in its last two stages of activity (during the last 600 ka) by characterizing petrologically and geochemically the various volcanic units that compose this massif and tying them to their relative time and space. The level of detail of the mapping involved in this chapter, together with a relatively complete geochemical and geochronological database, provided a unique opportunity to study the evolution of a complex composite volcano in Central America providing a better understanding on how volcanoes grow in a volcanic front.

2 The Study Area

Poás volcano units reported in this chapter enclose an area of ~477 km^2, 337 km^2 of which are covered by new LiDAR data and high-resolution orthophotos. The study area is limited by the Río Cuarto maar to the north, and the Alajuela thrust fault escarpment to the south (Fig. 1c). The rivers Tambor and Sarchí and those of Toro and Sarapiquí (Fig. 1c) define the eastern and western limits, respectively. The geologic formations and members can be subdivided into three sectors: north, south and central

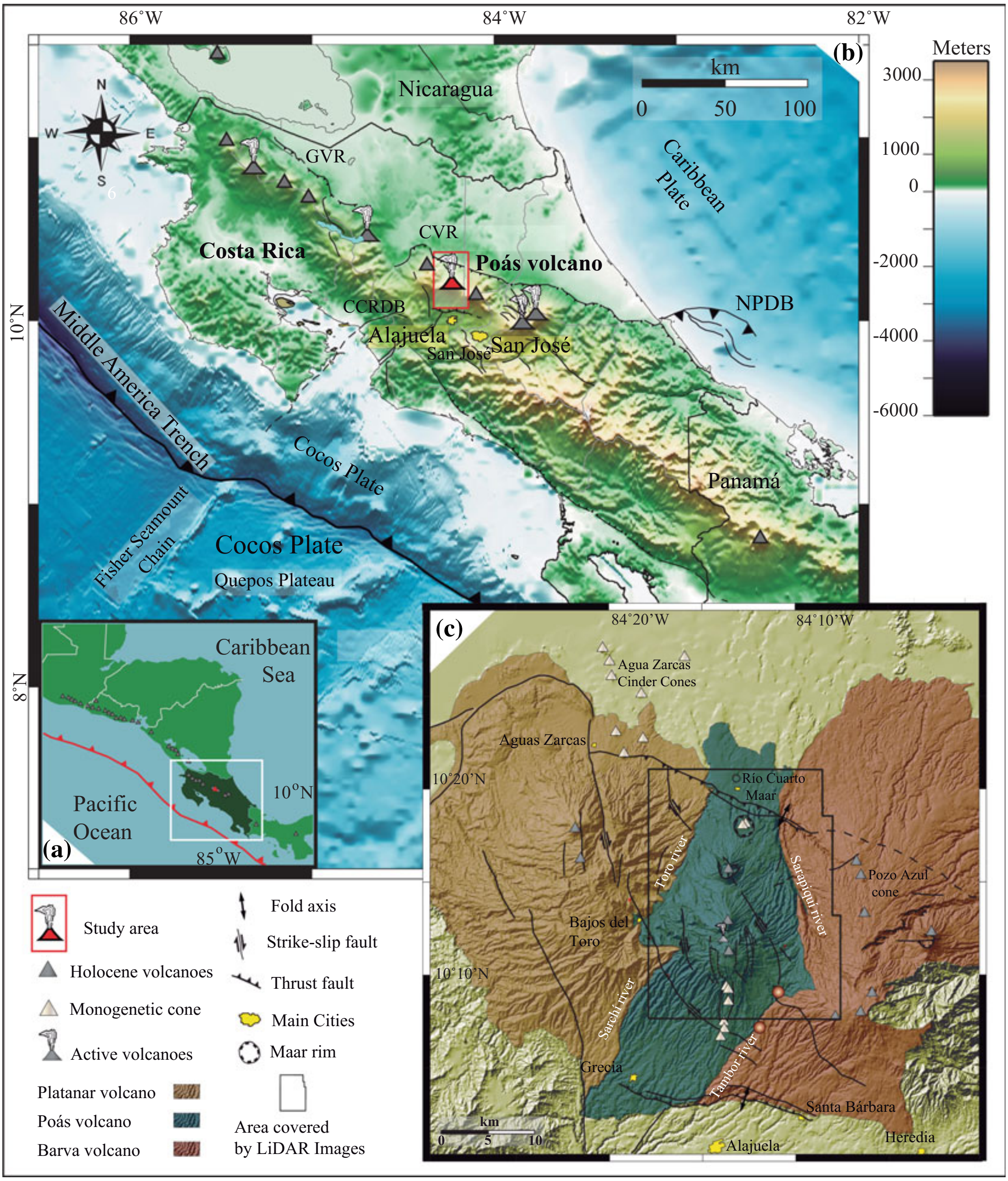

Fig. 1 **a** Map of the Central American Volcanic front and its tectonic setting; **b** digital elevation map of Costa Rica, showing the main volcanoes as dark grey triangles, with active volcanoes labeled with a plume. Bathymetry is from Ranero et al. (2005); **c** Poás volcano and its main tectonic structures from Montero et al. (2010). The black rectangle shows the area covered by LiDAR data used to build the presented digital elevation models

(present vent), based on the location of the vents from which they were expelled. Each one of these is composed by a different sequence of lavas, pyroclastic flows and fall deposits, and lahars among other volcanic materials. This chapter mostly focuses on the characterization of the various lava units mostly based on field and geomorphological observations (Fig. 2).

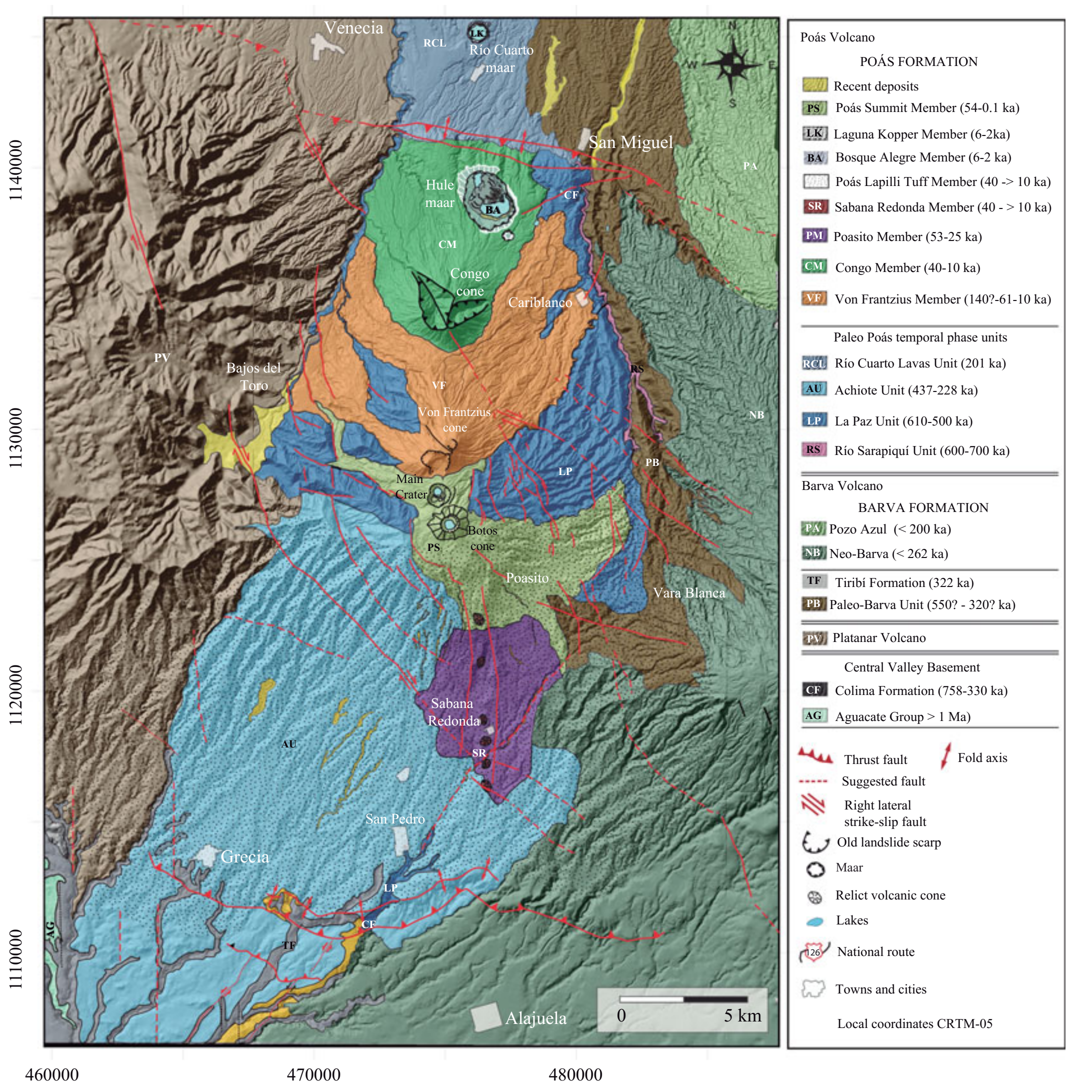

Fig. 2 Geological sketch map of Poás Volcano based on Prosser (1983), Alvarado and Climent (1985), Borgia et al. (1990), Rojas (1993), Alvarado and Carr (1993), Soto (1999), Campos et al. (2004), Gazel and Ruiz (2005), Montes (2007), Montero et al. (2010), Ruiz et al. (2010), Soto and Arredondo (2007), Huapaya and Rojas (2012), and new fieldwork. It is to note the location of Hule and Río Cuarto maars in the northern slopes of the volcano

2.1 Regional Setting

The CVR of Costa Rica is part of the Central American Volcanic front that extends parallel to the Middle American Trench from Guatemala to Costa Rica (Fig. 1). Its volcanic activity is due to the subduction of the Cocos Plate under the Caribbean Plate (Vannucchi and Mason Chapter "Overview of the Tectonics and Geodynamics of Costa Rica"). The convergence rate increases from ~83 mm yr^{-1} off southern Nicaragua to ~89 mm yr^{-1} off southern Costa Rica (DeMets et al. 2010). The lavas from Poás volcano as well as those from other volcanoes from central Costa Rica have an anomalous OIB signature when compared to the rest of the Central America

Volcanic arc and different models explained this peculiarity (e.g. Herrstrom et al. 1995; Russo and Silver 1994; Feigenson et al. 2004; Goss and Kay 2006; Hoernle et al. 2008). The latest model presented by Gazel et al. (2009) presented clear evidence that the observed OIB signature is derived from the Galapagos hot spot tracks subducting beneath Costa Rica and Panamá.

The summit of the Poás stratovolcano edifice is at 2708 m a.s.l. The currently active vent is located in the Main Crater, also known as Laguna Caliente. This crater holds one of the world's most acidic natural lakes, with a pH near zero and lies along a large (∼35 km long) N-S running volcano-tectonic cortical fracture (Prosser 1983; Soto and Alvarado 1989). There are other volcanic structures located in this north-south trending fissure that are geomorphologically distinctive and developed in different time periods and volcanic episodes from separated vents, e.g. the pyroclastic cones of Sabana Redonda, the Von Frantzius, Congo and Botos cones, and the explosive craters (maars) of Hule, Pata de Gallo and Río Cuarto. The scarps of the Alajuela and San Miguel reverse faults bound the northern and southern flanks of this complex stratovolcano. There are other tectonic structures (in particular strike-slip faults) to the east and west flanks of the volcano, characterized by historical destructive seismic activity. The major historical earthquakes occurred in 1772 (Mw 6.0), 1851 (Mw 6.0), 1888 (Mw 6.0), 1911 (Mw 6.0), 1912 (Mw 5.5), 1955 (Mw 6.1), and the Cinchona earthquake 2009 (Mw 6.2). All of them were located within the cities of Bajos del Toro, Fraijanes, Vara Blanca, and Poás (Peraldo and Montero 1999; Montero et al. 2010; RSN 2009).

The Main Crater of Poás has frequently been active during the last 200 years, with eruptions characterized by periodic phreatic explosions (Alvarado 2009; Mora Amador Chapter "Volcanic Hazard Assessment of Poás (Costa Rica) Based on the 1834, 1910, 1953–1955 and 2017 Historical Eruptions"). Since the active vent is located only 20 km from the second largest city of Costa Rica, Alajuela, where the main international airport is located, and just 30 km from the capital, San José, Poás represents a significant hazard for ash falling and ash clouds, which may affect air traffic, and lahars and acid rain. Additionally, since 1980, the Costa Rican Institute for Electricity (ICE) and private companies have developed hydroelectric projects in the northern side of Poás edifice, taking advantage of the high mean annual precipitation of the area (3,000–6,000 mm), and the steep slopes (between 25° and 30°) of the Poás volcano flanks.

3 Field and Analytical Methods

The geologic map of Poás volcano presented in this chapter (Fig. 2) is an upgrade of the one presented in Ruiz et al. (2010). Herein we completed the geological mapping and introduced more details on several areas that were not included in previous works, using LiDAR data and high-resolution orthophotos. In particular, the updated areas include the northwest sector of the Congo cone, the zone of Bajos del Toro, and the eastern flank of the volcano, where the road from Vara Blanca to San Miguel (Road 126) is located. Fieldwork was carried out in 2009 and 2013, taking advantage of the newly exposed outcrops after the landslides produced by the Cinchona earthquake (Ruiz et al. Chapter "Coseismic Landslide Susceptibility Analysis Using LiDAR Data PGA Attenuation and GIS: The Case of Poás Volcano, Costa Rica, Central America").

The complete geological map of Poás volcano (Fig. 2) is built on a digital elevation model (DEM) background based on two sources: the topographic maps to scale 1:50,000 of Poás, Barva, Río Cuarto, Quesada and Naranjo from the National Geographic Institute of Costa Rica (NGI), 520 km^2 of LiDAR data from Poás, and parts of Barva and Platanar volcanoes. The LiDAR data and orthophotos were obtained during an airplane flight in April 2009 by the Spanish and Costa Rican companies STEREOCARTO and AERODIVA, respectively, with an ALS50-II LEICA system, using a resolution of 3–4 points/m^2, to create a DEM with an x and y resolution of 50 cm and a z resolution of 15 cm (Ruiz et al. 2014). Differences in altitude between the images and the benchmarks of the topographic maps are less than 11 cm. The high quality of these data has an unprecedented resolution, which allowed us to identify volcanic features not recognizable by standard photogrammetric techniques. These images were processed using the commercial software packages Quick Terrain Modeler, SURFER 10.0 and GLOBAL MAPPER 13.0.

Several geologic studies were carried out in the northern part of area by the Costa Rican Institute of Electricity (ICE) to provide geologic characterization for hydropower projects. More than 155 borehole profiles from ICE were located on the NE and NW flanks of Poás volcano edifice, and were used in this chapter to identify the thickness of some of the lava flows from different volcanic units and members. In addition to the cores, information from a 6 km horizontal tunnel from the Cariblanco hydroelectrical project was also used. Cores and walls from the Cariblanco and Toro III tunnels were logged and sampled in detail for petrographic and geochemical characterization.

Furthermore, a geochronology database inclusive of several new $^{40}Ar/^{39}Ar$ and calibrated ^{14}C ages is here presented. The new $^{40}Ar/^{39}Ar$ age determinations were obtained on matrix separates at the Noble Gas Laboratory of Rutgers University, following the method described in Carr et al. (2007). These data were used to construct a new chronostratigraphic column of the Poás units (Fig. 3). Samples from each geologic

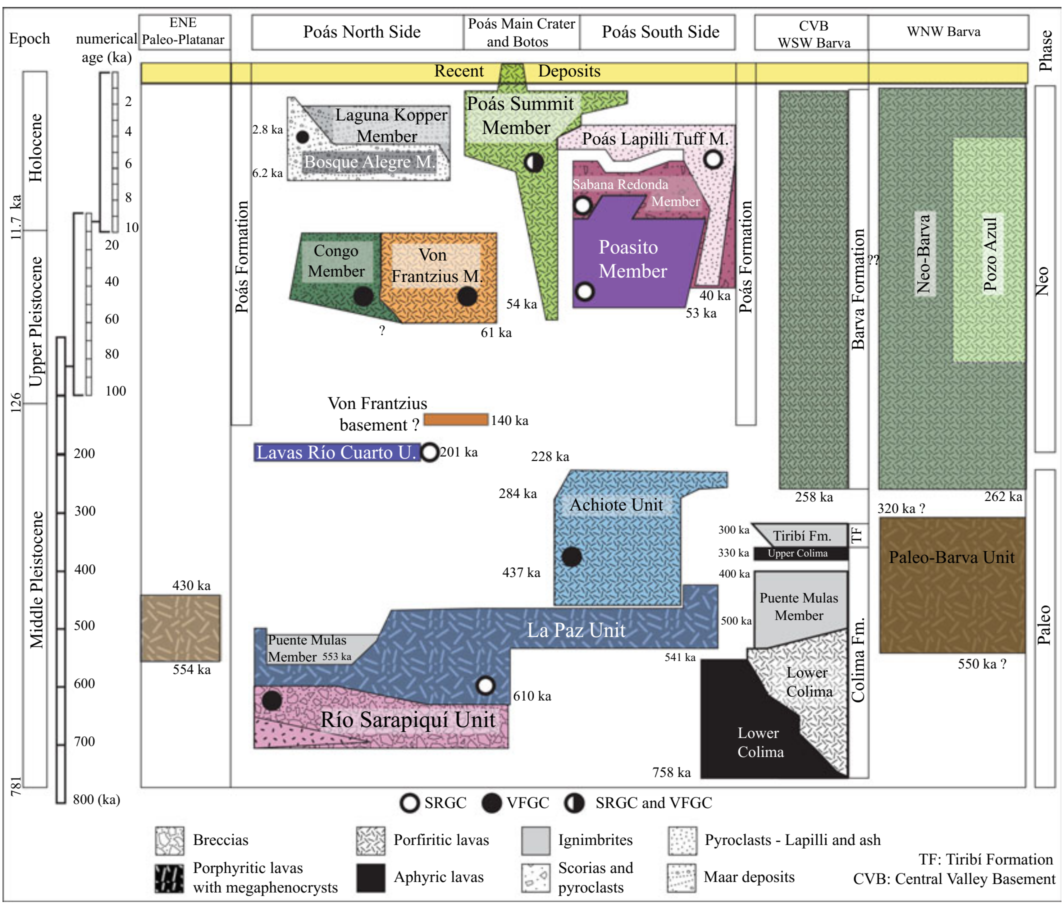

Fig. 3 Chronostratigraphic scheme of the Poás volcano products units. The main and subordinated lithologies are presented according to their geographical position relative to the Main Crater. Sabana Redonda Geochemical Component (SRGC), Von Frantzius Geochemical Component (VFGC). Colors of the units as in Fig. 2