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Architectural and Tectonic Control on the Segmentation of the Central American Volcanic Arc

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Abstract

Central America has a rich mix of conditions that allow comparisons of different natural experiments in the generation of arc magmas within the relatively short length of the margin. The shape of the volcanic front and this margin's architecture derive from the assemblage of exotic continental and oceanic crustal slivers, and later modification by volcanism and tectonic activity. Active tectonics of the Cocos-Caribbean plate boundary are strongly influenced by oblique subduction, resulting in a narrow volcanic front segmented by right steps occurring at ~150-km intervals. The largest volcanic centers are located where depths to the slab are ~90–110 km. Volcanoes that develop above deeper sections of the subducting slab are less voluminous and better record source geochemical heterogeneity. Extreme variations in isotopic and trace element ratios are derived from different components of the

subducted oceanic lithosphere. However, the extent that volcanoes sample these signatures is also influenced by lithospheric structures that control the arc segmentation.

- The architecture of Central America derives from the assemblage of exotic continental and oceanic crustal slivers modified by arc magmatism and tectonic processes.
- Active tectonics in Central America are controlled by oblique subduction.
- The lithospheric architecture and tectonics define the segmentation of the volcanic front, and thus the depth to the slab below a volcanic center.
- The composition of the subducted material is the main control of the along arc geochemical variations observed in Central American volcanoes.
- Geochemical heterogeneity in each segment is highlighted by extreme compositions representing the smaller centers with variations up to 65% of the total observed range.

1. INTRODUCTION

The geochemical evolution of Earth is controlled by element recycling in subduction zones. The breakdown of hydrated minerals during subduction results in fluids enriched in large ion lithophile (e.g., Rb, Ba, U, Pb, Sr) and other incompatible elements (e.g., Elliott et al. 1997, Manning 2004, Plank & Langmuir 1998). Together with sediment and slab melts, these fluids lower the solidus and viscosity of the mantle wedge, resulting in arc magmas (Plank & Langmuir 1993, Plank et al. 2009, Ryan & Chauvel 2014), building volcanic arcs as the surface expression of this global process. The filter effect of recycling in subduction zones is also critical to the element fractionation that controls the geochemical composition of the continental crust as well as the diversity of deep mantle sources sampled by intraplate volcanoes (Gazel et al. 2015, Hofmann 1997, Kelemen 1995, Mazza et al. 2019, Ryan & Chauvel 2014).

Although all convergent margins have unique characteristics based on their geologic history, Central America has a distinctly rich mix of conditions that allow comparisons of different natural experiments within the margin's relatively short span, from the Mexico-Guatemala border to central Costa Rica. Active tectonics of the Cocos-Caribbean plate boundary are strongly influenced by oblique subduction (e.g., Álvarez-Gómez et al. 2019, DeMets et al. 2000), resulting in six narrow volcanic front segments (Guatemala, El Salvador, NW Nicaragua, SE Nicaragua, N Costa Rica, and central Costa Rica) separated by right steps occurring at ∼150-km intervals (Stoiber & Carr 1973). The geochemical indicators of subducting sediments (e.g., Ba/La, U/Th, and $^{10}Be/^{9}Be$) define a maximum in NW Nicaragua and a minimum in central Costa Rica (Carr et al. 1990, 2003; Leeman et al. 1994). Finally, the lavas in the central Costa Rica volcanoes represent some of the most trace element–enriched lavas in the planet, with a clear ocean island basalt–like signature resulting from the interaction with subducting Galápagos tracks (e.g., Gazel et al. 2009, 2011; Hoernle et al. 2008).

The exceptional features of Central America made it the focus site of the National Science Foundation (NSF) MARGINS program and the German Science Foundation Collaborative Research Center (SFB 574), significantly expanding our knowledge of subduction systems, probably like no other arc on the planet. While these initiatives resulted in exciting discoveries on the modern volcanic front and its connection to the subduction factory, there is still a lack of integration of decades of geochemical and seismic research on the Central American Volcanic Arc with its lithospheric architecture and tectonic evolution. Here we produce a synthesis of the tectonic units that build the architecture and record the geologic evolution of Central America based on modern $^{40}Ar/^{39}Ar$, U–Pb, and radiolarian ages. We also produce a review of the modern seismic studies of the structure of the subduction system, the overriding crust, and the active tectonics of the margin. Finally, we examine the role of the architecture and active tectonics in the segmentation of the modern volcanic front, its control on vent distribution, volcano volume, and implications for the generation of the famous extreme geochemical variations along Central American volcanoes.

2. ARCHITECTURE AND TECTONIC EVOLUTION

The Central American Volcanic Arc developed in a tectonic puzzle of continental and oceanic crust represented by four domains: (*a*) North American Plate continental slivers, (*b*) the Guatemala Suture Zone (GSZ), (*c*) continental fragments within the Caribbean Plate, and (*d*) paleo-Pacific accreted oceanic complexes [serpentinite bodies and slivers of mid-ocean ridge basalts (MORBs), oceanic plateaus, and hotspot tracks]. Here we describe 25 distinct geotectonic units and their record of tectonic processes that together build the architecture of Central America (**Figures 1** and **2**).

Continental crust sequences that represent the southernmost extent of the North American Plate (**Figures 1*b*** and **2**) were classically grouped as the Maya Block (Dengo 1969, 1985; Donnelly et al. 1990). Recent studies suggest that four distinctive geotectonic units make up the architecture of this block: Chiapas, Maya, Izabal, and Jacalteco (**Figures 1*a*** and **2**). The Chiapas and Maya Units share similar ∼482–400 Ma basement complexes (Estrada-Carmona et al. 2012; Solari et al. 2010, 2013; Steiner & Walker 1996) as well as Late Paleozoic to Cenozoic overlapping sequences. Nevertheless, the discovery of ∼1.0–0.9 Ga boudins and inliers of crystalline rocks within the Chiapas metamorphic sequence (Cisneros de León et al. 2017, Weber et al. 2018) suggests that this unit shares a common origin with an orogenic event recorded in the Mexican continental terranes (Ortega-Gutiérrez et al. 2018). The Maya Unit is associated with a Pan-Africa/Brasiliano origin, supported by the ∼545 Ma shocked zircons found within the Cretaceous–Paleogene Chicxulub impact crater ejecta (Krogh et al. 1993) (**Figure 2**). Late Silurian–Early Devonian sequences from the southern Maya Unit also record an input from mid-Proterozoic complexes similar to those found in NW Amazonia and Mexico (Martens et al. 2010, Weber et al. 2012). An ∼70 Ma blueschist metamorphic facies overprint on Ordovician granites in central Guatemala implies that some sections of this unit underwent subduction during the Late Cretaceous (Solari et al. 2013).

The GSZ contains the present North American-Caribbean plate boundary (**Figure 1**). This E-W trending transform plate boundary accommodated at least ∼1,100 km of left-lateral, strike-slip motion over the past ∼50–45 Ma since the Cayman spreading center opened in the Caribbean (Leroy et al. 2000, Rosencrantz et al. 1988). This plate boundary separates the GSZ into the Izabal and Jacalteco geotectonic units to the north and Copán geotectonic unit to the south (Flores et al. 2013). The Izabal Unit includes a series of Early Cretaceous ophiolite slivers thrusted northward over the Jacalteco and Maya Units (e.g., Beccaluva et al. 1995). The Jacalteco Unit is separated from the Maya Unit by a thrust zone and includes mylonitic gneiss and schists, with relicts of eclogites and amphibolites (e.g., Ortega-Gutiérrez et al. 2007). These high-grade metamorphic sequences are thrust northward by superposed sheets of serpentinite-matrix mélanges with blocks of eclogites, blueschist, jadeitites, and amphibolites (Harlow et al. 2004). The high-grade schist and gneiss sequences yielded protolith crystallization ages of ∼450–440 Ma (Solari et al. 2011), similar to counterpart rocks of the Maya Unit (**Figure 2**). Subduction-related, high-pressure–low-temperature (HP-LT) metamorphic rocks within both units record ages of ∼101–65 Ma and ∼131–53 Ma, respectively (Brueckner et al. 2009, Flores et al. 2013, Harlow et al. 2004, Maldonado et al. 2018, Martens et al. 2012). The tectonic association of polymetamorphosed continental rocks, the record of HP-LT metamorphic facies, and obducted ophiolite sequences imply a collision in the Late Cretaceous of an island arc with the southern region of the North American Plate.

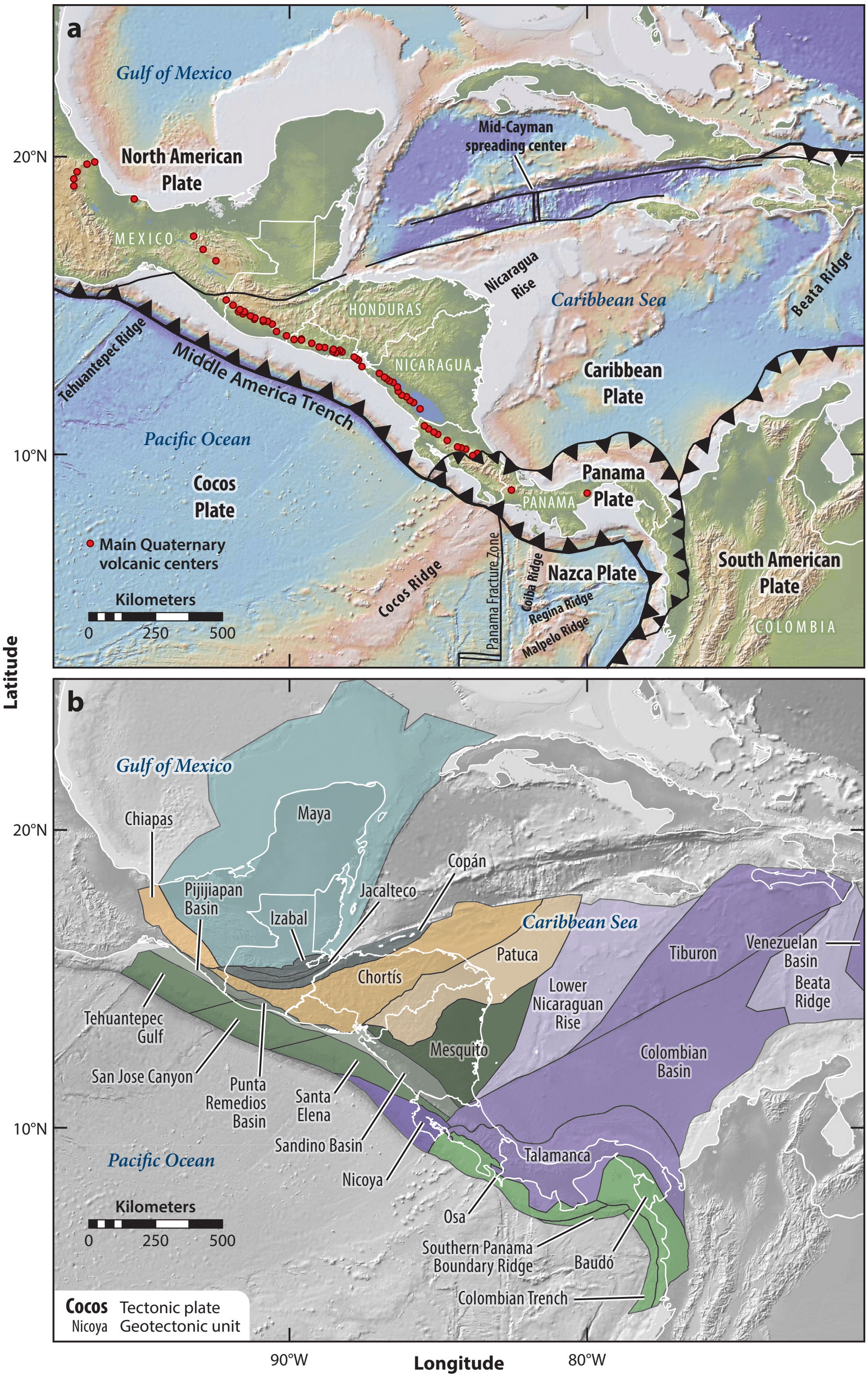


Figure 1

(*a*) Current tectonic scenario of the Central American Volcanic Front. (*b*) Geotectonic units of Central America and the western Caribbean.

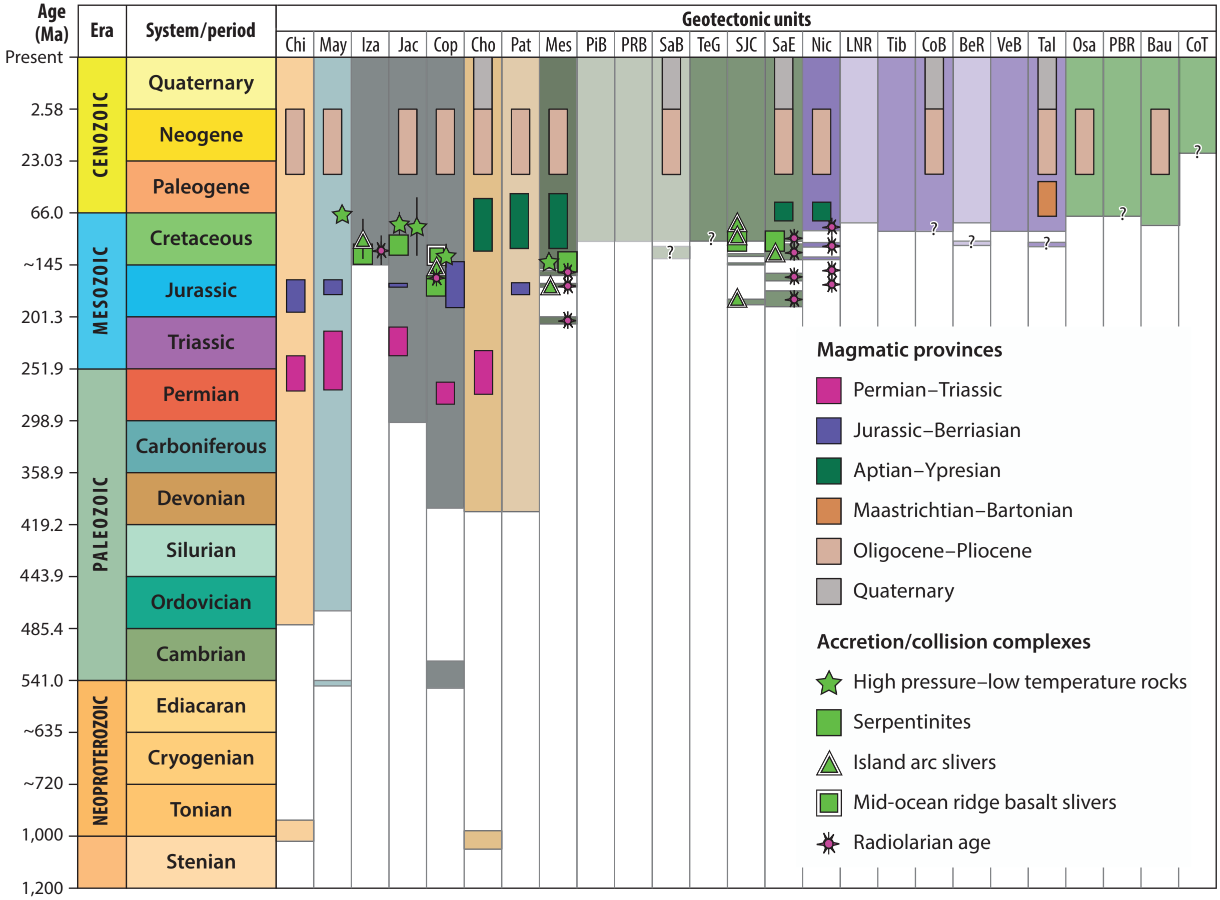


Figure 2

Correlation chart for the geologic record of the Central America geotectonic units. Note the timeline distribution of magmatic provinces and geologic features associated with accretion and collisional events. Key references and geochronological data are discussed in Sections 2 and 3. Abbreviations: Bau, Baudó; BeR, Beata Ridge; Chi, Chiapas; Cho, Chortís; CoB, Colombian Basin; Cop, Copán; CoT, Colombian Trench; Iza, Izabal; Jac, Jacalteco; LNR, Lower Nicaraguan Rise; May, Maya; Mes, Mesquito; Nic, Nicoya; Pat, Patuca; PBR, Southern Panama Boundary Ridge; PiB, Pijijiapan Basin; PRB, Punta Remedios Basin; SaB, Sandino Basin; SaE, Santa Elena; SJC, San Jose Canyon; Tal, Talamanca; TeG, Tehuantepec Gulf; Tib, Tiburon; VeB, Venezuelan Basin.

Rock sequences from the northwestern margin of the Caribbean Plate were classically grouped as Chortís blocks and ascribed as continental in nature (Dengo 1969, 1985; Donnelly et al. 1990). Recent studies suggest that the architecture of this block is composed of the Copán, Chortís, Patuca, and Mesquito geotectonic units (**Figures 1*b*** and **2**). An origin in southern Mexico for these complexes is the most accepted model, although South American and paleo-Pacific origins are also possible (Flores & Gazel 2020). The Motagua (San Agustín/Cabañas-Jubuco-Cuyamel) and Jocotán (Jocotán-Chamelecón-La Ceiba-Aguán) fault systems limit the Copán Unit to the north and south, respectively. This unit consists of ~555–520 Ma low-grade metasedimentary sequences (Torres-de León et al. 2012) (**Figure 2**). These sequences are thrusted by tectonic slivers of high-grade polymetamorphic sequences, metavolcanic bodies and associated metasediments, and serpentinite mélanges. The high-grade polymetamorphic sequences yielded an ~400 Ma protolith age and Late Cretaceous–Paleogene metamorphic ages (Ratschbacher et al. 2009). The metavolcanic bodies and associated metasediments include accretionary sequences with Late Jurassic paleo-Pacific radiolarian fauna (Chiari et al. 2006). This paleontological age is closer to the ∼156–155 Ma metamorphic ages from the metasediments but older than the ∼130 Ma igneous age recorded in an oceanic basaltic sliver (Geldmacher et al. 2007, Ratschbacher et al. 2009) (**Figure 2**). The serpentinite-matrix mélanges contain blocks of eclogites, blueschist, and jadeitites, with ages ranging from ∼158 to 113 Ma (Brueckner et al. 2009, Flores et al. 2013, Harlow et al. 2004, Tsujimori et al. 2006).

The Jalan and Guayape faults in central Honduras define the boundary between the Chortís and Patuca geotectonic units. These units share similar Mesozoic–Cenozoic volcano-sedimentary overlapping sequences. However, ∼1,017 Ma orthogneiss and ∼404–396 Ma metagranites and schists make the basement sequences of the Chortís Unit (Manton 1996, Ratschbacher et al. 2009) (**Figure 2**), while the age of basement sequence of the Patuca Unit is still not well constrained. Nevertheless, a potential Neoproterozoic to Early Paleozoic origin is consistent with dominating U–Pb zircon-age populations of ∼650–500 Ma and ∼400 Ma within Jurassic sandstones from the overlapping sequence (Flores & Gazel 2020, Molina-Garza et al. 2019).

The Mesquito geotectonic unit was initially defined as a composite terrane of paleo-Pacific origin that accreted to the Chortís and Patuca Units during the Cretaceous. Based on new studies, the architecture of this unit can be divided into seven distinct geotectonic units: the Mesquito, Santa Elena, San Jose Canyon, Tehuantepec Gulf, Pijijiapan Basin, Punta Remedios Basin, and Sandino Basin (**Figures 1*b*** and **2**). The Mesquito Unit outcrops south of Patuca, with a boundary located between Bocay and Siby fault systems in NE Nicaragua (Flores & Gazel 2020). In the northern section of this unit, the basement sequence consists of serpentinite mélanges that include meta-igneous and sedimentary sequences that record greenschist to eclogite-facies. Radiolarites associated with the greenstones contain Middle Jurassic radiolarians, and the HP-LT metamorphic blocks yielded ages of ∼149–131 Ma (Baumgartner et al. 2008, Escuder-Viruete et al. 2019, Flores et al. 2015). The rock sequences within the northern Mesquito Unit are synchronous to oceanic counterparts in the Copán Unit, suggesting a similar origin along the paleo-Pacific subduction zone. However, a major tectonic rearrangement was responsible for their structural juxtaposition, Copán to the north and Mesquito to the south of the continental slivers of Chortís and Patuca (**Figures 1*b*** and **2**). The southern section of the Mesquito Unit consists of highly deformed serpentinites and slivers of accreted hotspot tracks with Late Triassic paleo-Pacific radiolarites (Baumgartner et al. 2008).

The Santa Elena, San Jose Canyon, and Gulf of Tehuantepec geotectonic units compose more than 70% of the convergent margin between the Caribbean and Cocos Plates, making up most of the current modern forearc segment. Almost all their extensions are underwater, reducing their exposure to the Santa Elena peninsula in Costa Rica, Deep Sea Drilling Project (DSDP) Legs 67 and 84 in the San Jose Canyon, and one borehole in the Tehuantepec Gulf (**Figures 1*b*** and **2**). The Santa Elena Unit includes tectonic slivers of ∼177–174 Ma intraplate basalts, Early Jurassic to Early Cretaceous radiolarites, and trench-filling sediments (Bandini et al. 2011, Buchs et al. 2013). A massive ultramafic body intruded by ∼131–116 Ma pegmatitic gabbros and diabases tectonically overlies this sequence (Baumgartner & Denyer 2006, Gazel et al. 2006, Madrigal et al. 2015). The basement of DSDP Legs 67 and 84 boreholes in the San Jose Canyon Unit consists of serpentinites and basaltic slivers that yielded ages ranging from ∼219 to 80 Ma (Geldmacher et al. 2008) (**Figure 2**). The base of the SC-1 borehole in the Gulf of Tehuantepec Unit is composed of a Late Cretaceous conglomerate containing volcanic and tonalitic blocks (Sanchez-Barreda 1981). The Mesquito, Santa Elena, and San Jose Canyon's southern section contains equivalent synchronous sequences that indicate a long-lived accretion cycle during the Mid–Late Cretaceous (**Figure 2**).

The Pijijiapan, Punta Remedios, and Sandino geotectonic units are extensional, nonaccretionary-type, forearc basins (e.g., Noda 2016). The limited boreholes in these units yielded Late Cretaceous–Cenozoic sedimentary sequences. However, the base section of the Rivas-1 borehole in the Sandino Unit contains basaltic rocks and volcaniclastic sediments (INE 1995) that are likely an equivalent to the sequences of the Santa Elena Unit.

Slivers of paleo-Pacific oceanic plateaus build the basement of the Nicoya, Talamanca, Colombian Basin, Tiburon, Beata Ridge, Venezuelan Basin, and Lower Nicaraguan Rise geotectonic units (**Figures 1*b*** and **2**). These units were formerly grouped into the Chorotega and Chocó blocks (Escalante 1990). Nevertheless, modern studies shed light on distinct paleo-Pacific origins and a complex tectonic history (Madrigal et al. 2016). The ~95–83 Ma Caribbean Large Igneous Province (CLIP) composes most of this domain. This oceanic plateau is interpreted as the onset of the Galápagos Plume that collided with Central and South America during the Late Cretaceous, resulting in accretion (e.g., Hauff et al. 2000; Sinton et al. 1997, 1998). Extensive geochemistry and geochronological studies in the Nicoya Unit show a record of older oceanic plateau basalts of ~140–133 Ma, ~118–111 Ma, ~93–88 Ma, and ~84–77 Ma, which must require other paleo-Pacific sources (Hoernle et al. 2004, Madrigal et al. 2016, Whattam et al. 2016). Additionally, widespread Middle Jurassic to Lower Cretaceous radiolarites suggest an older oceanic basement for this unit (Denyer & Baumgartner 2006). The occurrence of basalts of ~114–105 Ma within the Talamanca, Tiburon, and Beata Ridge Units (Lissinna 2005, Loewen et al. 2013, Révillon et al. 2000) implies that older oceanic plateau events are also recorded in this domain (**Figure 2**). Younger magmatic events include the ~81–71 Ma Beata Ridge and ~55–56 Ma Lower Nicaraguan Rise (Dürkefälden et al. 2019, Révillon et al. 2000, Sinton et al. 2000).

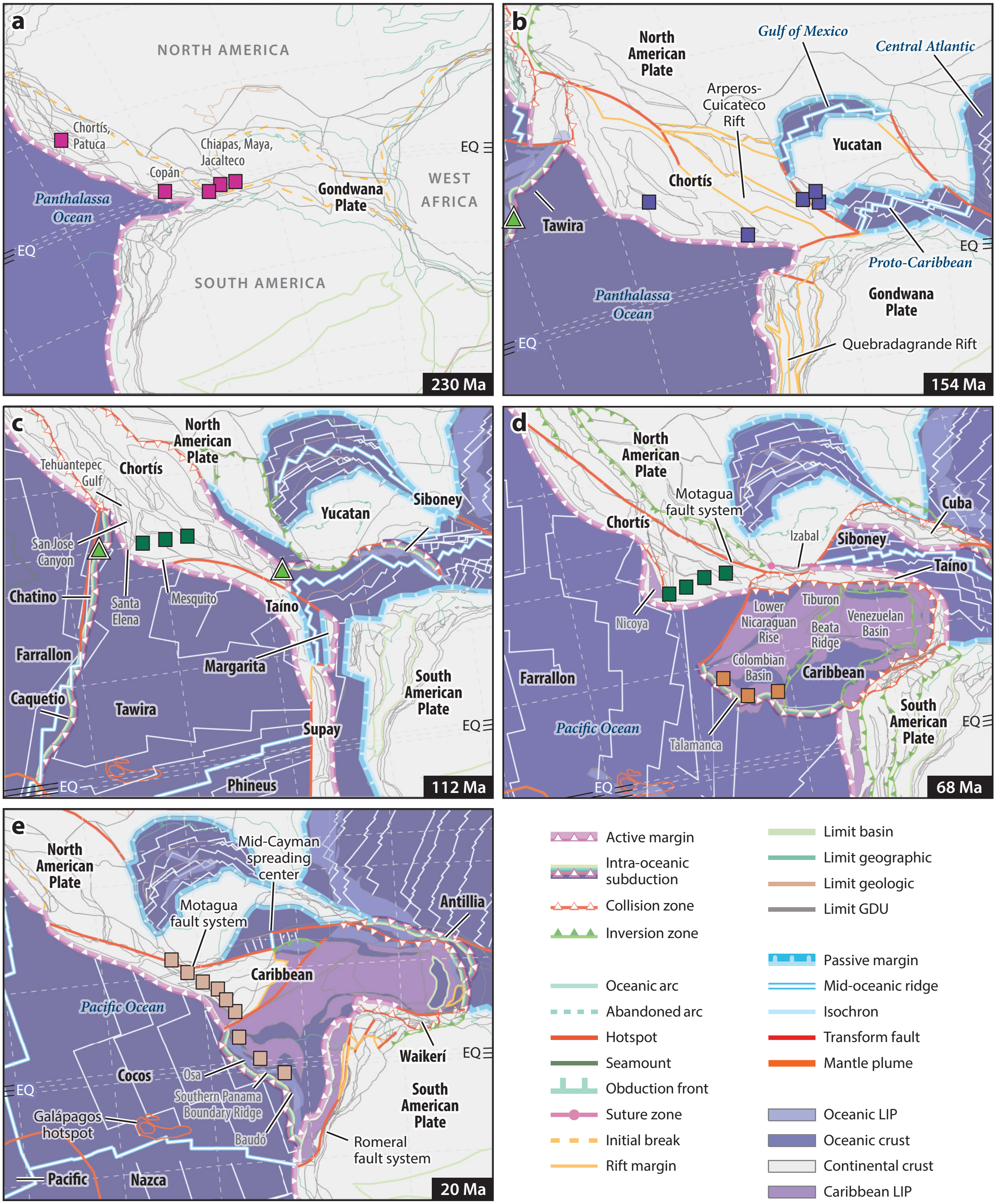
The Osa, Southern Panama Boundary Ridge, Baudó, and Colombia Trench constitute a domain of Cretaceous–Cenozoic (~84–21 Ma) accreted oceanic slivers, which includes sections linked to older Galápagos hotspot tracks such as the modern Cocos and Malpelo Ridges (**Figures 1*b*** and **2**). Sedimentary sequences overlapping the Osa Unit suggest that accretion initiated during the Eocene (Hoernle et al. 2002, Kerr et al. 1997, Lissinna 2005, Trela et al. 2015).

3. VOLCANIC ARC RECORD IN CENTRAL AMERICA

Central America contains an extensive record of volcanic arc–related rocks since the Permian that define six main magmatic provinces: (*a*) Permian–Triassic, (*b*) Jurassic–Berriasian, (*c*) Aptian–Ypresian, (*d*) Maastrichtian–Bartonian, (*e*) Oligocene–Pliocene, and (*f*) Quaternary (**Figure 2**).

The Permian–Triassic and Jurassic–Berriasian magmatic provinces occur on the continental geotectonic units (**Figures 1*b*** and **2**). The Permian–Triassic province consists of arc-related deformed granitoids and gneiss that yielded ages of ~283–215 Ma (Ratschbacher et al. 2009, Weber et al. 2007). In contrast, the Jurassic–Berriasian magmatic province includes rift-related continental volcanic sequences of ~196–140 Ma (Flores & Gazel 2020, Godínez-Urban et al. 2011, Ratschbacher et al. 2009). These two magmatic provinces suggest a changing tectonic scenario that evolved from a Cordilleran system to an extensional cycle associated with the opening of backarc basins such as the proto-Caribbean and the Gulf of Mexico (Flores 2009, Madrigal et al. 2016) (**Figure 3*a*,*b***).

Several slivers of paleo-Pacific Mesozoic island arc volcanic associations with Jurassic radiolarites occur within the Copán and Mesquito Units (**Figure 2**) and within in the GSZ (Flores et al. 2015). Equivalent units in the DSDP Leg 84 site 567A in the San Jose Canyon Unit yielded ~182 Ma (Geldmacher et al. 2008). Younger paleo-Pacific island arc sequences are also recorded in the Santa Elena Unit (125–110 Ma), DSDP Leg 67 site 494 (~112 Ma), and DSDP Leg 84 sites 567A and 569A (~83–80 Ma) (Geldmacher et al. 2008, Hauff et al. 2000, Whattam et al. 2016).



(Caption appears on following page)

Figure 3 (*Figure appears on preceding page*)

Kinematic plate tectonic reconstruction for Central America. (*a*) Final magmatic stage of the Permian–Triassic province within the Cordilleran orogenic system in the western margin of Gondwana supercontinent ca. 230 Ma. (*b*) Jurassic–Berriasian magmatic province localities along the rifted region and the active margin of the Chortís Plate ca. 154 Ma. Magmatic rocks from this province indicate the collapse of the Cordilleran Orogeny, which triggered extension of backarc basins in the Americas. These tectonic events are synchronous to the opening of the central Atlantic, proto-Caribbean, and Gulf of Mexico, as the accretion/collision of island arc systems. (*c*) The onset of the Aptian–Ypresian magmatic province along the southern margin of the Chortís Plate ca. 112 Ma. During this time, a back-inversion triggered westward subduction of the Americas backarc basins, and second accretion/collision of an island arc system occurred along the paleo-Pacific margin of the Americas. (*d*) Maastrichtian–Bartonian magmatic province arc initiation along the SW margin of the Caribbean Plate ca. 68 Ma. This magmatic onset predates the closure and suturing of the Americas backarc basins and the collision/docking of the Caribbean LIP into the Americas. (*e*) Oligocene–Pliocene magmatic province onset along the western margin of the Caribbean Plate ca. 20 Ma. Abbreviations: GDU, geodynamic unit; LIP, large igneous province. Figure adapted from Flores (2009) and Flores & Gazel (2020).

These arc slivers are interpreted as the record of the collision of exotic paleo-Pacific island arcs, or arc sequences obducted during the closure of a local backarc basin (Flores 2009, Flores et al. 2015) (**Figure 3*b*,*c***).

Flores & Gazel (2020) defined the Aptian–Ypresian (∼124–50 Ma) magmatic province as a sequence of calc-alkaline volcanic and intrusive rocks (**Figure 2**). This province occurs in the Chortís, Patuca, and Mesquito Units, and it marks the initiation of a volcanic arc system that postdates the collisions in the southern margin of Patuca and subsequent exhumation of HP-LT rocks in northern Mesquito (Flores et al. 2015). The presence of Late Cretaceous–Paleogene ignimbrites, tuffs, and andesite-bearing conglomerates likely extends this province to the Santa Elena and Nicoya Units (**Figures 2** and **3*c***).

The Maastrichtian–Bartonian magmatic province occurs in the CLIP's southern margin in the Talamanca Unit (**Figures 1** and **2**). This magmatic sequence consists of ∼71–39 Ma volcanic and intrusive rocks of tholeiitic and minor calc-alkaline compositions, where the oldest rocks are interpreted as the record of subduction initiation in this tectonic unit (Montes et al. 2012, Wegner et al. 2011). Even though the Aptian–Ypresian and Maastrichtian–Bartonian magmatic provinces contain sequences of similar age, there is no evidence that both arc systems formed in the same subduction system or that they were ever connected (**Figures 2** and **3*d***).

The Oligocene–Pliocene and Quaternary magmatic provinces define the modern volcanic arc system in Central America (Flores & Gazel 2020). The Oligocene–Pliocene province (**Figures 2** and **3*e***) is distributed in almost all the geotectonic units of the study area and displays a general migration of magmatic activity toward the trench since the Miocene, which is attributed to the Cocos Plate slab rollback (Saginor et al. 2011). In contrast, almost all modern volcanic centers of the Quaternary active volcanic front are restricted to the Chortís, Sandino Basin, Santa Elena, and SW area of Colombian Basin units (**Figure 1*b***). Middle to late Miocene contractional deformation records the change from oblique to orthogonal subduction of the Cocos Plate below the Caribbean Plate (Mescua et al. 2017) (**Figure 3*e***), which culminated with the collision of the Central American arc with South America ∼7.1 Ma (Coates et al. 2004). While the origin of the Talamanca Unit is oceanic, this unit evolved into a juvenile continental block since the Miocene because of the interaction with Galápagos tracks, which resulted in a thick (>30 km) and buoyant crust, with a clear continental crust geochemical signature (Gazel et al. 2009, 2015, 2019) (**Figure 4*a***).

4. THE ACTIVE VOLCANIC FRONT

Most volcanic activity in Central America occurs along the narrow volcanic front that arises above the subducting Cocos Plate slab. Volcanoes on top of the Cocos Plate are closely spaced and

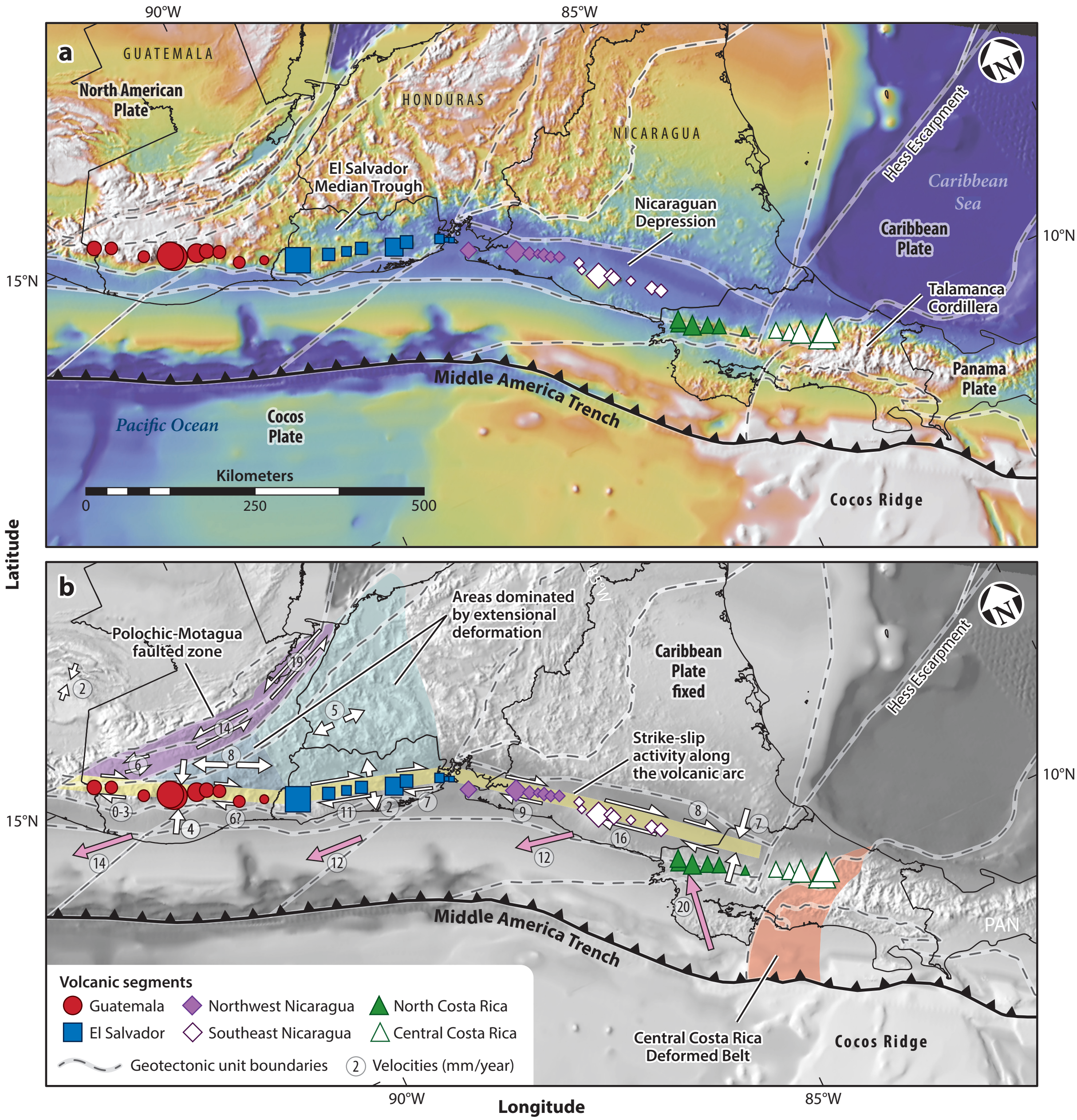


Figure 4

Volcanic segments and tectonics of Central America. (*a*) Residual bathymetry and gravity map of subduction zones from Bassett & Watts (2015). (*b*) Kinematic model from Álvarez-Gómez et al. (2019). The dashed lines represent the boundaries of the geotectonic units detailed in **Figures 1** and **2**. The white arrows represent the sense of motion for extension, shortening, and strike-slip displacement in the colored zones. The pink arrows display the horizontal motion of the specific geotectonic units in the forearc region.

active, whereas the volcanoes arising from the Nazca-Panama convergence are widely spaced and dormant. Calk-alkaline magmas dominate the volcanic front, but there are also isolated alkaline fields in the backarc of Honduras, Nicaragua, and Costa Rica and on top of the subduction of the Panama Fracture Zone (Gazel et al. 2011, Heydolph et al. 2012). In this section, we focus on the active volcanic front and its relation with the subducting slab, the lithospheric architecture, and active tectonics.

The Cocos-Caribbean oblique subduction has strongly influenced the active tectonics along the modern convergent margin, resulting in the volcanic front's segmentation into six narrow fragments (**Figure 4**). Right steps occurring at ∼150-km intervals separate these segments: Guatemala, El Salvador, NW Nicaragua, SE Nicaragua, N Costa Rica, and central Costa Rica (Stoiber & Carr 1973). The Guatemala and El Salvador segments occur in the western margin of the Chortís Unit. The volcanic activity in the Guatemala segment ends at the boundary with the Polochic-Motagua Fault Zone at the North American-Caribbean transform plate boundary (**Figures 1** and **4**). The El Salvador segment is located in the western margin of the El Salvador Median Trough, a less geomorphologically prominent continuation of the Nicaraguan Depression (Carr 1976, Funk et al. 2009) (**Figure 4*a***). The NW and SE Nicaraguan segments occur within the Sandino Basin Unit and the Nicaraguan Depression (**Figure 4**). The N Costa Rica volcanic segment sits on the boundary of the Sandino Basin, Mesquito, and Santa Elena geotectonic units. In contrast, the central Costa Rica segment occurs in the western margin of the Colombian Basin geotectonic unit and is limited on the northwest by an inland structure parallel to the Hess Escarpment and on the southeast by the Central Costa Rica Deformed Belt (**Figure 4**).

4.1. Tectonic Inheritance, Active Faulting, and Vent Distribution

The pioneering application of plate tectonics to Central America by Molnar & Sykes (1969) estimated a N30°E convergence for the Cocos-Caribbean plate boundary, consistent with the slip vectors of thrust earthquakes. Global models of plate kinematics including NUVEL-1 (DeMets et al. 1994) provided a similar result, but the motion of the Caribbean Plate was unconstrained. With the arrival of the Global Positioning System (GPS), this problem was resolved (e.g., DeMets et al. 2000), constraining the current Cocos-Caribbean pole of rotation and supporting the observation that the slip vectors of thrust earthquakes along the Cocos-Caribbean margin are deflected about 10° clockwise from the plate convergence direction. This deflection results from the partition of Cocos-Caribbean plate convergence into a trench normal component and an oblique component.

Destructive earthquakes occurred in a narrow zone along the volcanic front, creating a boundary that isolates the forearc geotectonic units (Santa Elena, San Jose Canyon, and the Gulf of Tehuantepec) from the Caribbean Plate (**Figures 1** and **4*b***). The forearc is migrating approximately N60°W at a rate of 12–14 mm/year (Álvarez-Gómez et al. 2019, DeMets 2001). LaFemina et al. (2009) found lower velocities and an increase from 7.7 mm/year in Costa Rica to 8.8 mm/year in El Salvador. Kobayashi et al. (2014) suggested that the impact of the Cocos Ridge into southern Costa Rica is the cause of tectonic forearc escape at a rate of ∼11 mm/year westward. The forearc motion is accommodated by shallow earthquakes along the volcanic front, the largest of which have magnitudes generally less than 6.5, posing a significant hazard due to their shallow depth and proximity to population centers, and because they are sometimes accompanied by volcanic eruptions (Alvarado et al. 2017).

There are large variations in how the oblique or trench parallel component is accommodated by interactions of large volcanic centers, active faults, and tectonic boundaries (**Figure 4**). In central Guatemala, northern Honduras, and western El Salvador, the proximity to the North American-Caribbean plate boundary, defined by the E-W striking Polochic-Motagua fault systems (**Figures 1*a*** and **4**), leads to the formation of extensional regions characterized by N-S grabens (Álvarez-Gómez et al. 2019) and the termination of the volcanic front (**Figure 4*b***). These grabens are major structures hosting destructive earthquakes and accommodating up to 8 mm/year of E-W extension (Guzmán-Speziale 2010). Trench parallel strike-slip faults are not obvious in most of the Guatemala volcanic segment, but the prominent right-lateral strike-slip Jalpatagua fault (Carr 1976) in southeastern Guatemala likely accommodates the trench parallel motion in that segment of the arc. Stratovolcanoes in Guatemala form short N-S alignments with strong geochemical gradients (Halsort & Rose 1991). Major silicic eruptions occur north of the stratovolcanoes, and there is an apparent progression of activity to the youngest, most active volcanoes at the southern end of these alignments (Rose et al. 1999). Several major grabens in northern Central America have diffuse areas of backarc volcanism, including cinder cone fields, fissure vents, and small shield volcanoes (Walker & Gazel 2014).

The volcanic segment in El Salvador has a lesser degree of obliquity, and the trench parallel motion occurs on the El Salvador Fault Zone, a broad discontinuous dextral strike-slip fault system parallel to the volcanic front and just north of it (Martínez-Diíaz et al. 2004). Corti et al. (2005) defined en échelon right-lateral strike-slip fault segments oriented E-W and a slip rate of ∼11 mm/year for the El Salvador Fault Zone (**Figure 4*b***). Volcanic activity is spatially confined to the fault segments and absent in the intervening pull-apart basins.

Canora et al. (2014) defined rates for the El Salvador Fault Zone of approximately 3 and 6 mm/year. Their analysis of the active faults indicates a transtensional stress regime for the current activity. However, the presence of several large fault scarps is inconsistent with that deformation and requires an earlier period of extension and development of a graben structure (**Figure 4*b***). Canora et al. (2014) proposed that El Salvador underwent a similar geodynamic evolution as proposed by Weinberg (1992) for the Nicaraguan Depression: an initial phase of extension normal to the arc causing arc-parallel depressions, followed by the present arc-parallel right-lateral strike-slip system. This proposed evolution is consistent with analog experiments (Alonso-Henar et al. 2014). Tectonically, the El Salvador segment and Tecuamburro and Moyuta volcanoes from the Guatemala segment locate in the western margin of the El Salvador Median Trough, a continuation of the Nicaraguan Depression (Funk et al. 2009) (**Figure 4**) .

In Nicaragua, obliquity is at a maximum, and yet arc-parallel strike-slip faults are either not present or inactive and buried by young volcanic deposits (LaFemina et al. 2002). Several destructive earthquakes occurred on faults that strike transverse to the margin. Earthquake aftershock zones and focal mechanism determinations find strike-slip faulting and N-S striking normal faults (Alvarez et al. 2018). Most Nicaraguan earthquakes and active volcanoes occur within the Nicaraguan Depression along the narrow zone occupied by the volcanic front. The earthquakes along the volcanic front cluster in swarms, sometimes accompany eruptions, and occur on NW-SE and N-S faults. Few earthquakes occur along the margins of the Nicaraguan Depression, and they preferentially have N-S striking normal fault mechanisms (Alvarez et al. 2018). Areas of active extension coincide with the right step between the SE and the NE Nicaragua volcanic segments (**Figure 4**). The best example is the Managua Graben (e.g., Weinberg 1992), but Lake Nicaragua and the Gulf of Fonseca also may have extensional structures given that they are the lowest points along the Nicaraguan Depression (Stoiber & Carr 1973).

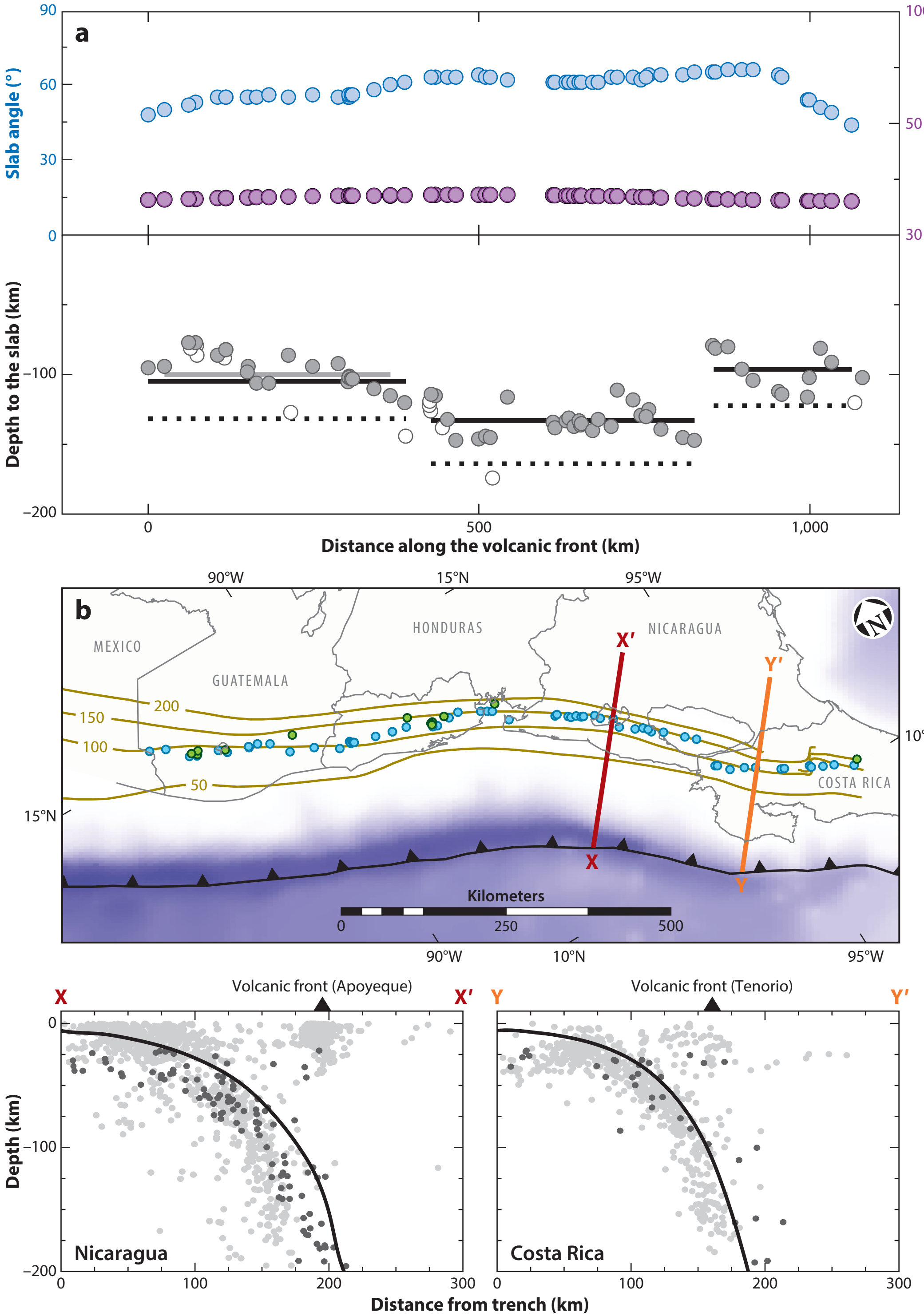
Weinberg (1992) inferred a three-phase neotectonic history for Nicaragua from the analysis of outcrop to macroscale structures. The earliest phase (Late Miocene to early Pliocene) is defined from arc parallel anticlines along the Pacific coastal plane and indicated arc normal compression; the second phase (Pliocene–Pleistocene) was arc normal extension that created the Nicaraguan Depression, a half graben extending the length of the Nicaraguan Margin. The present phase is dominated by strike-slip faulting with a right-lateral node parallel to the margin and a left-lateral node normal to the margin. The present stress field is consistent with a forearc sliver moving NW, but evidence for actual arc parallel faults is lacking (**Figure 4**). There is abundant evidence for left-lateral strike-slip faulting normal to the arc but only in the narrow zone of the volcanic front. Efforts to reconcile the actual faulting with the GPS evidence of northwest movement of a forearc sliver have called upon variants of bookshelf faulting (Cailleau et al. 2007, LaFemina et al. 2002), but the strike-slip faults bounding classic bookshelf fault blocks are absent. Alvarez et al. (2018) noted that there are many transverse left-lateral faults in the Nicaraguan Depression and suggested a nearly continuous distribution of transverse faults that link to the margins of the Nicaraguan Depression with normal faults.

The N Costa Rica volcanic segment has a similar assemblage of neotectonic features, a narrow volcanic front with associated active faulting including N-S extensional features such as several vent alignments and arc parallel right-lateral strike-slip earthquakes in western Costa Rica (Marshall et al. 2000, Montero et al. 2017) (**Figure 4*b***). Nevertheless, the main arrangement of vents is consistent with the strike of the boundary between the Nicoya, Santa Elena, and Mesquito geotectonic units (**Figures 1** and **4*b***). Arenal is the only active volcano between N Costa Rica and central Costa Rica, in an ∼70-km section of decrease in volcanic activity that maps the change to subduction of crust overprinted by Galápagos tracks. In the central Costa Rica segment, the impact of the Cocos Ridge (e.g., Kobayashi et al. 2014), the proximity of the Nazca Plate, and the development of a nascent convergence zone in the North Panama Deformed Belt resulted in more complex tectonics. Magma production in central Costa Rica is significant and resulted in voluminous volcanic centers culminating with the Irazu-Turrilaba twin volcanic centers (Gazel et al. 2019). The main vents keep a NW-SE orientation, and multiple secondary vents are arranged N-S of the main structures. The Central Costa Rica Deformed Belt (Marshall et al. 2000) defines the southeastern edge of the Caribbean Plate and places the southeastern third of Costa Rica in the Panama microplate (**Figures 1*a*** and **4*b***). This area includes the Talamanca Cordillera (**Figure 4*a***), dominated by plutonic activity and limited Quaternary volcanic activity. Igneous rocks less than 12 Ma in the Talamanca Cordillera have clear geochemical signatures consistent with the juvenile continental crust, interpreted as the result of the interaction of this section of the margin with older Galápagos tracks (Gazel et al. 2019). This young continental block is flanked by contractional NW-SE structures in both the Pacific and the Caribbean sides (Montero et al. 2017).

4.2. Images of the Mantle and Deep Crust

The subducted Cocos slab's morphology, imaged as the surface of the Wadati-Benioff Zone (**Figure 5**), is a critical tectonic parameter affecting magma generation and transport beneath Central America. Several subducting slab models suggest a uniform dip and depth of the Wadati-Benioff Zone from Guatemala to N Costa Rica, where it becomes shallower due to the subduction of Galápagos tracks (e.g., Hayes et al. 2013, Protti et al. 1994, Syracuse & Abers 2006). Syracuse et al. (2008) relocated hypocenters using the TUCAN (Tomography Under Costa Rica and Nicaragua) project to clearly define the morphology of the seismic zone beneath Nicaragua and western Costa Rica. There is little change in the Wadati-Benioff Zone morphology across Nicaragua and central Costa Rica where the dip of the seismic zone gradually shallows (Lücke & Arroyo 2015, Protti et al. 1994). The 14-km right step in the volcanic front between NW and SE Nicaragua and the sizeable right step of 40 km between the SW Nicaragua and NW Costa Rica Volcanic Fronts are not reflected in the seismicity (**Figure 5**). Given that there are no significant changes in the subducting slab, the architecture, tectonic history, and active crustal deformation must therefore control volcanic segmentation in Central America.

Negative seismic anomalies in the subducting lithospheric mantle offshore Nicaragua suggest a high hydration grade promoted by bending faults (van Avendonk et al. 2011). Earthquakes



(*Caption appears on following page*)

Figure 5 (*Figure appears on preceding page*)

Slab model for the subducting Cocos Plate slab. (*a*) Change of slab angle and depth to the slab along the volcanic front and approximate slab age. (*b*) Slab contours every 50 km and locations of profiles across Nicaragua and Costa Rica. (*c*) Slab cross section at the beginning of the SE Nicaragua volcanic segment and at the termination of the N Costa Rica volcanic segment. The dark gray dots represent earthquakes from global earthquake catalogs, and the light gray dots are from local Central American catalogs; the heavy black lines indicate the best slab model (additional information available in Syracuse & Abers 2006). Figure adapted from Syracuse & Abers (2006).

at 100–150 km depth beneath Nicaragua show a high-frequency late P-wave arrival at regional stations (Abers et al. 2003). A low-velocity waveguide 2.5–6 km thick at the top of the downgoing plate, about 15% slower than surrounding mantle, can explain this delayed phase. Such low velocities are consistent with ∼5 wt% H_2O in the subducted crust, two to three times the hydration inferred for other slabs (Abers et al. 2003). Seismic tomography by Syracuse et al. (2008) supports the P-wave results indicating a wet Nicaraguan slab, adding new information about the nature of the mantle beneath the volcanic arc including interesting contrasts between Nicaragua and Costa Rica. Beneath Nicaragua, a slow layer deep within the downgoing slab extends from the surface to 80–140 km depth, interpreted as serpentinization of the subducting lithospheric mantle (Syracuse et al. 2008, van Avendonk et al. 2011). Beneath the Nicaraguan volcanoes, this signal is a vertical region of high V_p/V_s spanning the mantle wedge and possibly indicating melt presence. These features are not resolvable beneath Costa Rica. Finally, beneath and behind the volcanic front in Nicaragua and Costa Rica is a low P-wave velocity zone extending to depths as great as 140 km. Nicaragua is characterized by a hydrated slab, a hot wedge, and a well-defined region of likely melt beneath the volcanoes. In contrast, Costa Rica has less pervasive hydration throughout the slab and wedge; a possibly slightly cooler wedge; and a broader, less concentrated region of melt (Abers et al. 2014, Rychert et al. 2008, Syracuse et al. 2008). Volatile studies on olivine-hosted melt inclusions record higher water concentration in Nicaragua than in Costa Rica, consistent with the presence of a more hydrated mantle wedge beneath Nicaragua (Benjamin et al. 2007, Sadofsky et al. 2008, Wade et al. 2006).

MacKenzie et al. (2008) imaged the crust across the active arc in Nicaragua and Costa Rica using receiver functions to estimate crustal thickness and V_p/V_s. Crustal thickness ranges from 25 to 44 km with the thinnest crust (25 km) directly beneath the Nicaraguan Volcanic Front, while the thickest crust lies in the Nicaraguan backarc and beneath the Costa Rican Arc (38 km) (**Figure 6**).

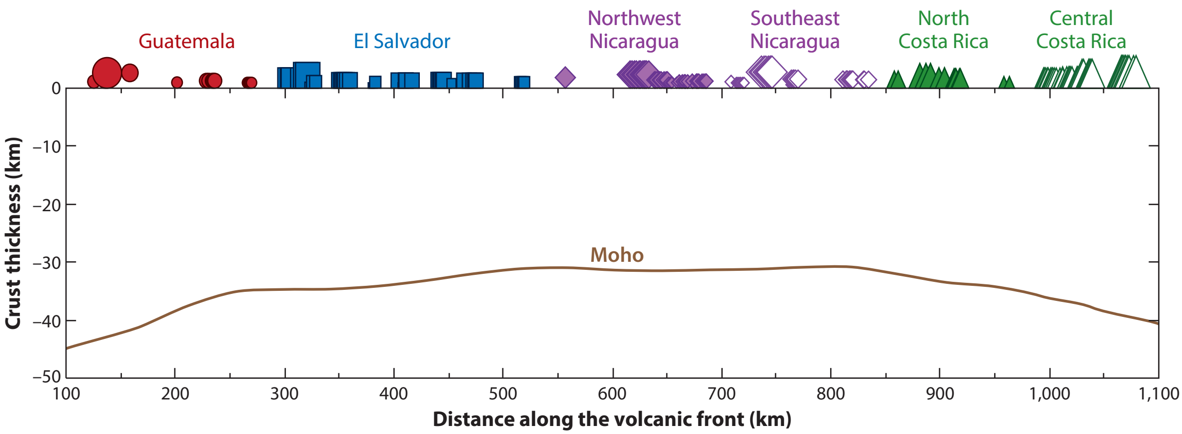


Figure 6

Crust thickness along the Central American Volcanic Front. The sizes of the volcano symbols are proportional to volcano edifice volumes from Carr et al. (2014). Crustal thickness from MacKenzie et al. (2008) and Lücke (2014).

At 80 km depth, the low-velocity anomaly interpreted as melt in NW Nicaragua lies beneath the volcanic arc, but in SE Nicaragua, it lies 40–50 km trenchward. This indicates that between 80 km depth and the surface, the location of the melt is shifting toward the thinnest crust in southern Nicaragua, rather than ascending vertically. MacKenzie et al. (2008) speculated that ascending magmas in Nicaragua are focused from the site of their generation to the thinnest crust rather than rising vertically from their source. This does not appear to be the case in Costa Rica. Lücke (2014) extended the map of crustal thickness across Central America using a global geopotential model derived from satellite gravity and altimetry and Moho constraints from receiver function analysis of teleseismic earthquakes (e.g., MacKenzie et al. 2008). At the broader scale of this investigation, most segments of the volcanic front lie along the maximum thickness of the crust. Outside of Nicaragua, the relatively stable positions of past volcanic fronts appear to have built deep crustal roots, while in Nicaragua, the present volcanic front has moved substantially trenchward during the Late Cenozoic (Saginor et al. 2011). Explosive silicic volcanism occurs throughout Central America in variable amounts, but in a general way, the distribution of silicic magmas correlates with crustal thickness, which is at a minimum in Nicaragua (**Figure 6**).

4.3. Implications for Geochemical Variations and Volcanic Productivity Along the Volcanic Front

Along Central America the isotopic and incompatible trace element geochemistry of the volcanoes is strongly controlled by the subducting input (e.g., Carr & Gazel 2017, Eiler et al. 2005, Carr et al. 1990, Gazel et al. 2019, Heydolph et al. 2012, Patino et al. 2000, Saginor et al. 2013). Subducting sources include hemipelagic sediment, carbonate sediment, altered oceanic crust (AOC), and serpentinized mantle (Eiler et al. 2005, Ranero et al. 2003). The AOC comes in at least two distinct flavors; for most of the margin the current subducted crust beneath the volcanoes formed at the East Pacific Rise and is normal MORB with hydrothermal alteration. For central Costa Rica, the dominant AOC component derives from Galápagos-related tracks (e.g., Gazel et al. 2009, 2018; Hoernle et al. 2008). The upper plate provides a variable lithospheric column above an asthenospheric wedge of depleted mantle with possible veins of enriched mantle (Feigenson & Carr 1986, Gazel et al. 2011). In Central America, the sediment on the subducting Cocos Ridge is not accreted, and subduction erosion is currently active (e.g.,Vannucchi et al. 2003, von Huene & Scholl 1991).

DSDP cores revealed a lower carbonate section and an upper hemipelagic section. The most unequivocal source for historic lavas is the uppermost hemipelagic mud on the Cocos Plate where ^{10}Be is concentrated (Morris & Tera 1989, Tera et al. 1986). The relatively high values of ^{10}Be/^{9}Be at most Central American volcanoes require that the uppermost sediments are at least partly preserved during subduction; Arenal and Irazú volcanoes in central Costa Rica are possible exceptions (Tera et al. 1986). The hemipelagic sediment section has very high concentrations of Ba and U, whereas the carbonate section has high Ba and Sr and very low contents of rare earth elements and Th (Patino et al. 2000). As a result, the carbonates have very high Ba/Th and low U/La and the hemipelagic sections have the reverse. The contributions of the sediment section appear in many lava suites as apparent binary mixing arrays between these two end members. The transition from carbonate sedimentation to hemipelagic sedimentation is reflected in the geochemistry of Tertiary volcanics in El Salvador and Nicaragua that lack the distinctively high U/Th found in the active volcanoes (Plank et al. 2002, Saginor et al. 2013). Finally, evidence of serpentinization of the subducting Cocos Plate offshore Nicaragua (Ranero et al. 2003), ^{18}O ratios in Nicaraguan olivines, and thus fluids from the serpentinized subducting mantle are also important subducting inputs.

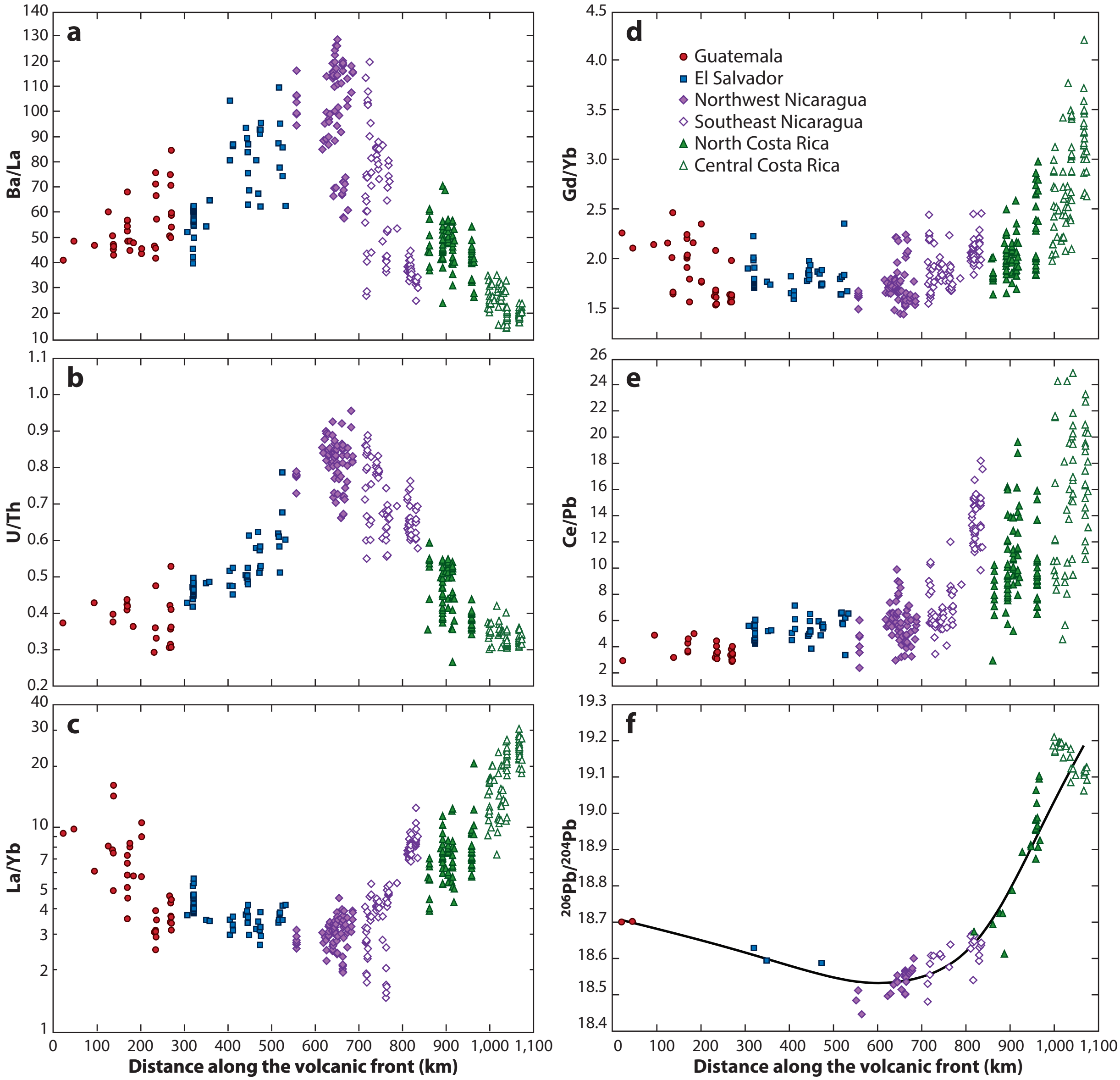


Figure 7

Geochemical variations along the volcanic front in Central America. Note the maximum fluid-derived signatures present in Nicaragua and the least in central Costa Rica, where the lavas record the input of a recycled intraplate component. Data from Carr et al. (2014).

Feigenson & Carr (1986) provided the first clear examples of fractionation-independent regional variation with Sr and Nd isotope ratios, both of which have maxima in Nicaragua. This symmetrical variation is clearly seen in several other parameters, especially trace element ratios, such as Ba/La and U/Th (**Figure 7*a*,*b***). The regional change in Ba/La was initially thought of as continuous change in a process with invariant inputs (e.g., Carr et al. 1990). This proved wrong for Costa Rica because the Cocos Plate subducting there has a very different oceanic crust, one

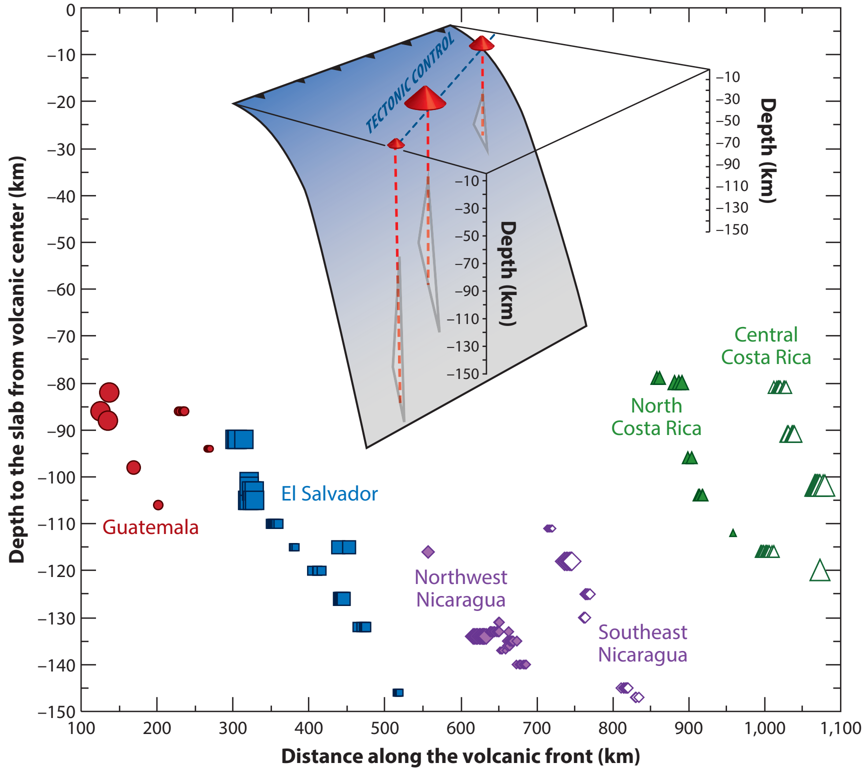


Figure 8

Depth to the subducting slab along the volcanic front in Central America controlled by the different volcanic segments (**Figure 4**). The sizes of the volcano symbols are proportional to volcano edifice volumes (Carr et al. 2014). The most voluminous volcanoes are above ~90–110 km from the slab. Note how volume correlates with the position of the volcanic center and its relation to the subducting slab. The inserted schematic figure shows this correlation.

strongly modified by subducting Galápagos tracks. The interaction with melts from the subducting Galápagos volcanics resulted in magmas in central Costa Rica enriched in trace elements (e.g., La/Yb > 10) (**Figure 7*c***), with a clear participation of a garnet-rich source (Gd/Yb > 2.5) (**Figure 7*d***) and with intraplate affinities (Ce/Pb up to 24) (**Figure 7*e***) and radiogenic isotopes (e.g., $^{208}Pb/^{206}Pb > 18.8$) (**Figure 7*f***), that mimic the subducting Galápagos tracks offshore (Gazel et al. 2009, Hoernle et al. 2008).

Because the strikes of the volcanic segments in Central America are typically rotated counterclockwise from the strike of the slab, each volcanic line has progressively deeper depths to the slab from northwest to southeast (**Figure 8**). Bolge et al. (2009) defined an axis of volcanic productivity by connecting the six largest volcanic centers (Atitlán Caldera, Santa Ana, San Cristobal, Masaya, Rincón de la Vieja, and Irazú-Turrialba) (**Figures 8** and **9**). This axis is nearly parallel to the coastline and has the same strike as the slab. All the major volcanoes fit within a 40-km-wide zone whose boundaries are drawn parallel to the axis, and all the segments cut diagonally across it. The largest volcanic centers are located ~90–110 km on top of the slab, and volcanoes that develop above deeper parts of the subducting slab are less voluminous (**Figure 8**). Taking into consideration each volcanic segment, the largest volcano is generally the second volcanic center, and the centers' volumes decrease toward the SE; the exception is central Costa Rica, where the trend is

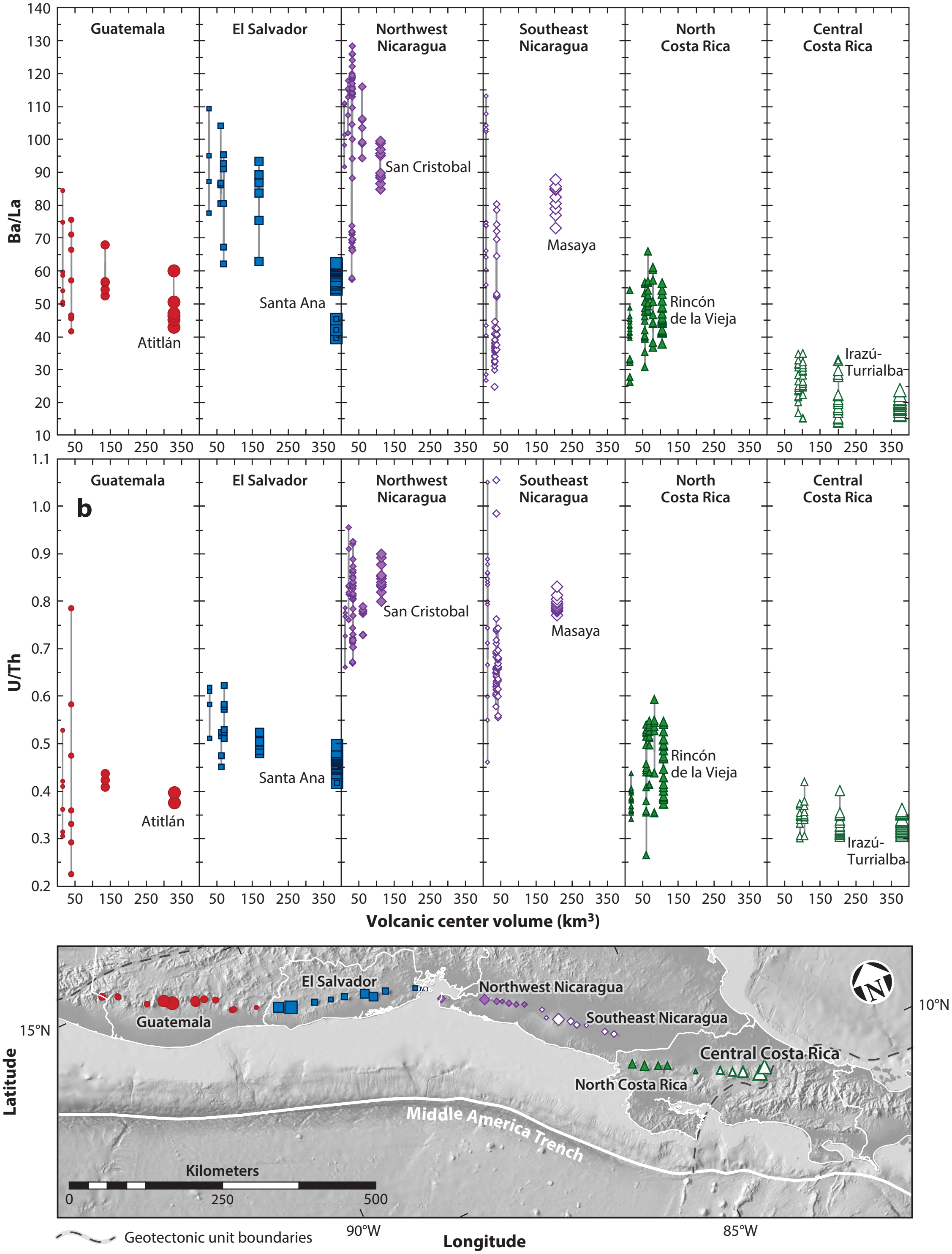


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Figure 9 (*Figure appears on preceding page*)

Geochemical variations along the volcanic front in Central America that indicate subduction components (*a*) Ba/La and (*b*) U/Th, plotted as a function of volcano volume. Extreme compositions represent the smaller centers with variations up to 65% of the total observed range of Ba/La (*a*) and U/Th (*b*), while the largest volcanoes (Atitlán Caldera, Santa Ana, San Cristobal, Masaya, Rincón de la Vieja, and Irazú-Turrialba) are characterized by less than 15% variation. (*c*) Central America Volcanic Front segments. The symbol of the volcano's size is proportional to its volumes. Data from Carr et al. (2014).

inverted, increasing productivity in correlation with the geochemical indicators (**Figure 7*c*–*f***) of a more fertile Galápagos source influencing the volcanic output (Gazel et al. 2019).

To better observe the effects of segmentation in the development of the volcanic front, we plotted geochemical ratios (Ba/La, U/Th) known to trace the slab fluid input as a function of volcanic center volume. We found that the geochemical heterogeneity is highlighted by extreme compositions representing the smaller centers with variations up to 65% of the total observed range, while very limited variations in these ratios characterize the largest volcanoes (<15%) (**Figure 9**). This can be explained if the volcanoes above the slab at ∼90–110 km are at the right spot where the mantle wedge gets the most components from the slab, resulting in high degrees of partial melting that homogenize the different subduction components, which are more evident in smaller vents. Alternatively, the large volcanoes homogenize the subduction signatures by having large plumbing systems and magma reservoirs, and lithospheric processes control their size. Nevertheless, independent of the process, the obliquity of the segments defines the location of the volcanoes along this margin and becomes the main control on the depth to the subducting slab and the potential to sample different subduction components.

5. SUMMARY AND FUTURE WORK

While there is a record of volcanic activity in northern Central America since the Permian and in southern Central America since the Mesozoic, the current volcanic arc started in the Oligocene. Since then, the axis has migrated toward the trench, likely due to slab rollback. The active volcanic front results from a combination of slab components, lithospheric architecture, and tectonics. Active tectonics are controlled by oblique subduction, resulting in a narrow volcanic front segmented by right steps occurring at ∼150-km intervals. The composition of the subducted slab is the main control of the along arc geochemical variations. The lithospheric architecture and tectonics control the segmentation and the depth to the slab below a volcanic center. All the major volcanoes fit within a 40-km-wide zone, where the largest volcanic centers are located ∼90–110 km on top of the slab. Volcanoes that develop above deeper sections of the subducting slab are less voluminous and have a higher potential to record geochemical heterogeneity. Regional geochemical variations have extremes from the high slab contributions in Nicaragua, where fluid and sediment signatures present the most extreme values, to central Costa Rica, where there is a clear Gálapagos component. Oblique subduction also resulted in a forearc escape toward the NW, right-lateral strike-slip faults along the volcanic front, and the generation of depressions in Nicaragua and El Salvador. Future work in Central America should focus on understanding across-arc geochemical variations to better elucidate the role of different mantle components that can be obscured by subduction. A better sampling of some centers, mainly focusing on their detailed evolution and their relation to close-by centers, will improve our understanding of the margin by allowing separation of subduction and lithospheric processes on the composition of arc volcanoes. Comprehensive studies of the tectonic evolution and the volcanic history in Chiapas (southern Mexico) and Panama are also necessary to recognize this margin's evolution and its connection to global processes. Finally, new volatile element studies using modern sampling protocols and analytical techniques are required to elucidate volatile cycles along and across the margin and their implications for volcanic hazards.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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