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Résumé de l'article

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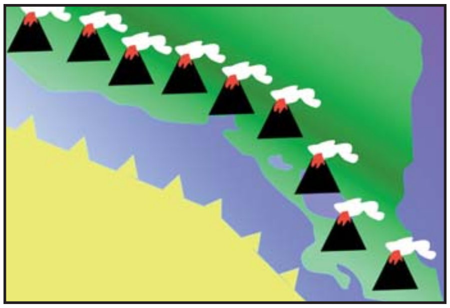
SERIES



Igneous Rock Associations 13. Focusing on the Central American Subduction Zone

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SUMMARY

Central America has recently been an important focus area for investigations into the complex processes occurring in subduction zones. Here we review some of the new findings concerning subduction input, magma production and evolution, and resultant volcanic output. In the Nicaraguan portion of the subduction zone, subduction input is unusually wet, likely caused by extensive serpentinization of the mantle portion of the incoming plate associated with bending-related faulting seaward of the Middle America trench. The atypical influx of water into the Nicaraguan section of the subduction zone ultimately leads to a regional maximum in the degree of mantle melting. In central Costa Rica, subduction input is also unusual in that it includes oceanic crust flavored by the Galapagos plume. Both of these exotic subduction inputs are recognizable in the compositions of magmas erupted along the volcanic front. In addition, Nicaraguan magmas bear a strong chemical imprint from subducting hemipelagic sediments. The high-field-strength-element depletions of magmas from El Salvador through Costa Rica are related to local variations in the depth to the subducting Cocos plate and, therefore, to segmentation of the volcanic front. Minor phases, probably amphibole or rutile, control these variable depletions. Silicic magmas erupted along the volcanic front exhibit the same along-arc geochemical variations as their mafic brethren. This and their mantle-like radiogenic isotopic compositions suggest the production of juvenile continental crust all along the Central American subduction zone. Punctuated times of enhanced magmatic input from the mantle may aid in crustal development.

SOMMAIRE

L'Amérique centrale a récemment été le lieu de recherches sur les processus complexes se produisant dans les zones de subduction. Ici nous passons en revue certaines découvertes sur nature des intrants de subduction, la production et l'évolution des magmas, ainsi que les extrants volcaniques résultants. Dans le segment nicaraguayen de la zone de subduction, les intrants de subduction sont exceptionnellement humides, probablement à cause de la serpentinisation généralisée de la portion mantélique de la plaque en subduction, fissurée par flexure dans partie marine de la fosse océanique de l'Amérique centrale. L'afflux atypique en eau dans le segment nicaraguayen de la zone de subduction induit ultimement un maximum régional de la proportion de fusion du manteau. Dans la portion centrale du Costa Rica l'intrant de subduction est lui aussi atypique en ce qu'il comprend une croûte océanique teintée par le panache des Galápagos. Ces deux intrants de subduction atypiques sont répercutés dans la composition des magmas éjectés le long du front volcanique. En outre, les magmas nicaraguayens affichent une forte empreinte chimique héritée des sédiments hémipélagiques en subduction. Les appauvrissements en éléments à fortes liaisons atomiques des magmas, du El Salvador jusqu'au Costa Rica, sont liés à des variations localisées de la profondeur de la plaque en subduction de Cocos, et donc, à la segmentation du front volcanique. Des phases mineures, probablement amphibole et rutile, déterminent ces appauvrissements variables. Les magmas siliceux éjectés le long du même front volcanique montrent les mêmes variations géochimiques le long de l'arc que leur contrepartie mafique. De plus, les compositions radiogéniques de leurs contreparties mantéliques évoquent la

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production d'une croûte continentale juvénile le long de la zone de subduction de l'Amérique centrale. Des épisodes d'accroissements ponctuels des intrants magmatiques du manteau peuvent contribuer au développement d'une croûte.

INTRODUCTION

The Central American subduction zone is awash with volcanologic and petrologic diversity over its 1100 km-long length (McBirney 1969; Carr et al. 1982, 2003, 2007a, b; Carr 1984; van Wyk de Vries et al. 2007). Over the past decade and a half, encouraged in part by relative political stability, this diversity has been examined in finer detail, yielding considerable new and important insights into magmatic and volcanic processes occurring in the Central American subduction zone. Recognizing and understanding the intricacies of this subduction zone is crucial, as all of Central America's population is at risk from earthquakes and volcanic eruptions (Ewert and Harpel 2004; Witham 2005; Dilley et al. 2005; Auker et al. 2013). In this brief review, we will summarize some of the newer insights concerning Central American magmatism and volcanism with the aim of stimulating future research along this fascinating convergent margin. We acknowledge that this review is in no way comprehensive, but it does provide an overall view of the efforts to understand Central American magma genesis. There have also been many recent, significant studies concerning other aspects of the Central American subduction zone and its volcanoes, including neotectonics, eruption dynamics, tephra fallout, volatile emissions, volatile cycling, volcanic stratigraphy, groundwater – volcano interactions, volcanic surveillance, and hazard assessments.

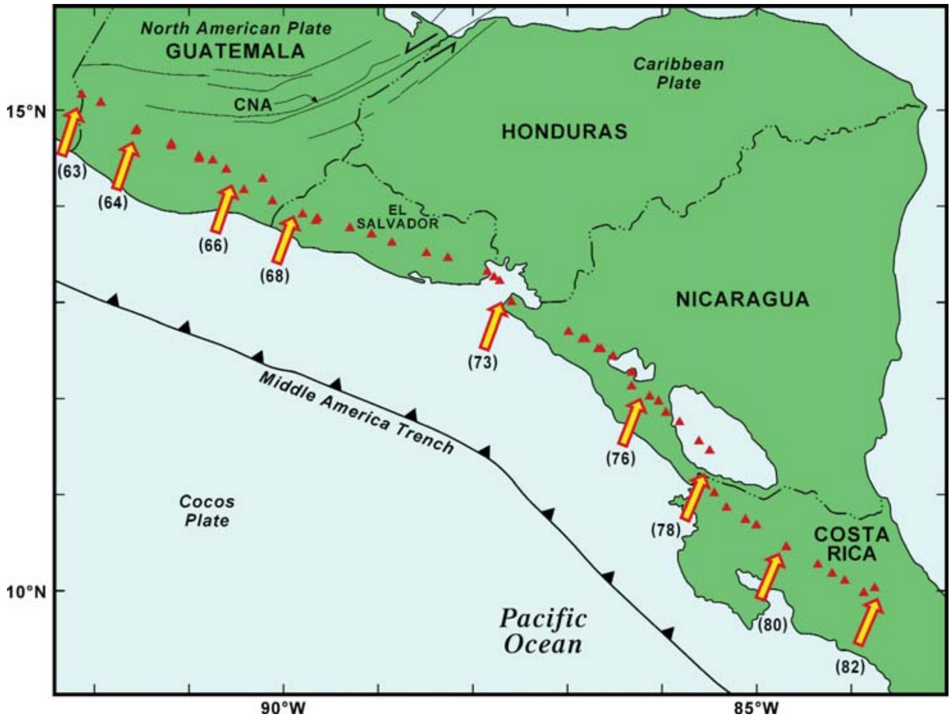

Figure 1. Simplified tectonic framework for Central America. Red triangles are Quaternary volcanic complexes of the volcanic front. Arrows point to discontinuities (segment boundaries) in the volcanic front after Carr et al. (2007b). Arrows also indicate estimated convergence directions (from Syracuse and Abers 2006). Numbers in parentheses are calculated convergence rates also from Syracuse and Abers (2006). CNA is the Caribbean – North American plate boundary.

TECTONIC, GEOLOGIC, AND VOLCANIC FRAMEWORK

In this paper we will restrict the boundaries of the Central American subduction zone (CASZ) to the region that is experiencing subduction of the Cocos Plate beneath the Caribbean Plate, i.e. from the Guatemala – Mexico border to central Costa Rica (Fig. 1). The rate of Cocos – Caribbean convergence slightly increases southeastward along the trench from about 6 to 9 cm/yr (DeMets 2001; Syracuse and Abers 2006) and slab dips below the active volcanoes are variable, with the steepest dips beneath Nicaragua (Carr 1984; Protti et al. 1995; Syracuse and Abers 2006; Syracuse et al. 2008; MacKenzie et al. 2010). Slab depths are also greatest beneath Nicaragua (Syracuse and Abers 2006). Oceanic crust formed at the East Pacific Rise (ca. 25 Ma), with a normal mid-ocean ridge basalt composition, subducts from Guatemala to northern Costa Rica, whereas 15–20 Ma oceanic crust that formed at the Cocos – Nazca Spreading Center and was overprinted by Galapagos hotspot tracks, subducts in central Costa Rica (Werner et al. 1999; O'Connor et al. 2007). There is no evidence of sediment accretion along the CASZ, so all sediments are assumed to be subducted into the mantle (Aubouin et al. 1984; Ranero and von Huene 2000; Moritz et al. 2000). The total thickness of subducting sediments is similar all along the CASZ, as is their lithologic architecture, which consists of an overlying sequence of hemipelagic muds underlain by carbonate oozes (von Huene et al. 1980; Plank and Langmuir 1993, 1998; Kimura et al. 1997; Patino et al. 2000). The presence of the North American – Caribbean plate boundary transecting Guatemala (Fig. 1) adds an appreciable level of complexity to the tectonics of the northern CASZ (Burkart and Self 1985; Guzmán-Speziale 2001; Lyon-Caen et al. 2006; Rogers and Mann 2007; Álvarez-Goméz et al. 2008; Rodriguez et al. 2009; Walker et al. 2011).

Although Cocos – Caribbean convergence has a much longer history (Mann et al. 2007; Gazel et al. 2009, 2011; Alvarado and Gans 2012), in this review we will restrict discussion to Quaternary volcanism, focusing on the volcanic front where volcanism has been overwhelmingly concentrated during the Quaternary (Carr et al. 1982, 2003, 2007a). Crustal thickness below the volcanic front is shallowest in Nicaragua (ca. 25–30 km) and thickens to ca. 35–45 km toward the extremities of the CASZ (Carr 1984; Carr et al. 1990, 2003; Sallarès et al. 2001; MacKenzie et al. 2010; Lücke et al. 2010). According to Rogers et al. (2007), much of the volcanic front, from southeastern Guatemala through Nicaragua, has been built on the southern Chortis terrane, which is floored by a post-Paleozoic arc-type or ocean-crust basement (Geldmacher et al. 2008). The northwestern portion of the volcanic front in central and northwestern Guatemala, by contrast, is likely underlain, at least in part, by rocks of the central Chortis terrane, which has a continental Paleozoic to Precambrian substrate (Dengo 1985; Rogers et al. 2007). The crustal character below the other end of the volcanic front, in Costa Rica, is also distinctive, being thickly anchored by rocks of the Caribbean Large Igneous Province, interpreted as a product of the Galapagos plume head (Hauff et al. 1997, 2000; Sallarès et al. 2001).

Magmas erupted along the volcanic front range from basalts to rhyolites that largely exhibit the characteristic elemental signatures of a subduction zone origin (Carr et al. 1982, 2003, 2007b; Carr 1984; Walker 1989; Leeman et al. 1994; Patino et al. 2000; Sadofsky et al. 2008). Along most of the CASZ there is a bimodal distribution of compositions with peaks in basalt – basaltic andesite and rhyolite (Vogel et al. 2006).

THE VOLCANIC FRONT – ARE ALL SEGMENTS EQUALLY CREATED?

The Central American volcanic front is thought to be among the world's most active volcanic belts (Bluth and Rose 2002). The application of high precision $^{40}Ar/^{39}Ar$ dating to a larger number of volcanic rocks associated with Quaternary volcanism in Central America (Rose et al. 1999; Vogel et al. 2004; Carr et al. 2007a; Escobar-Wolf et al. 2010; Singer et al. 2011; Alvarado and Gans 2012) has allowed renewed appraisals of extrusive and magmatic fluxes along the volcanic front. Carr et al. (2007a) estimate that extrusion rates along the Nicaraguan and Costa Rican segments of the front are roughly equivalent within error. In contrast, Bolge et al. (2009) calculate raw eruptive volumes along the volcanic front in Costa Rica that are substantially larger than those in Nicaragua, consistent with earlier inferences that Costa Rica has had a greater volcanic flux than Nicaragua (Carr 1984; Carr et al. 1990). For their volume estimates, Bolge et al. (2009) incorporate important new data from Kutterolf et al. (2008b) on tephras erupted along the CASZ over the past 322,000 years. According to Kutterolf et al. (2008b), these Plinian products account for approximately 65% of the total magmatic output in the CASZ. Moreover, their analysis indicates that the overall magma fluxes have been greatest in the northern half of the CASZ (Kutterolf et al. 2008b; Fig. 2a). If, however, the volume estimates of Bolge et al. (2009) are taken as a simple reflection of overall magmatic flux, then Costa Rica emerges as the most magmatically productive portion of the CASZ (Fig. 2b).

All of the investigations summarized in this section so far have

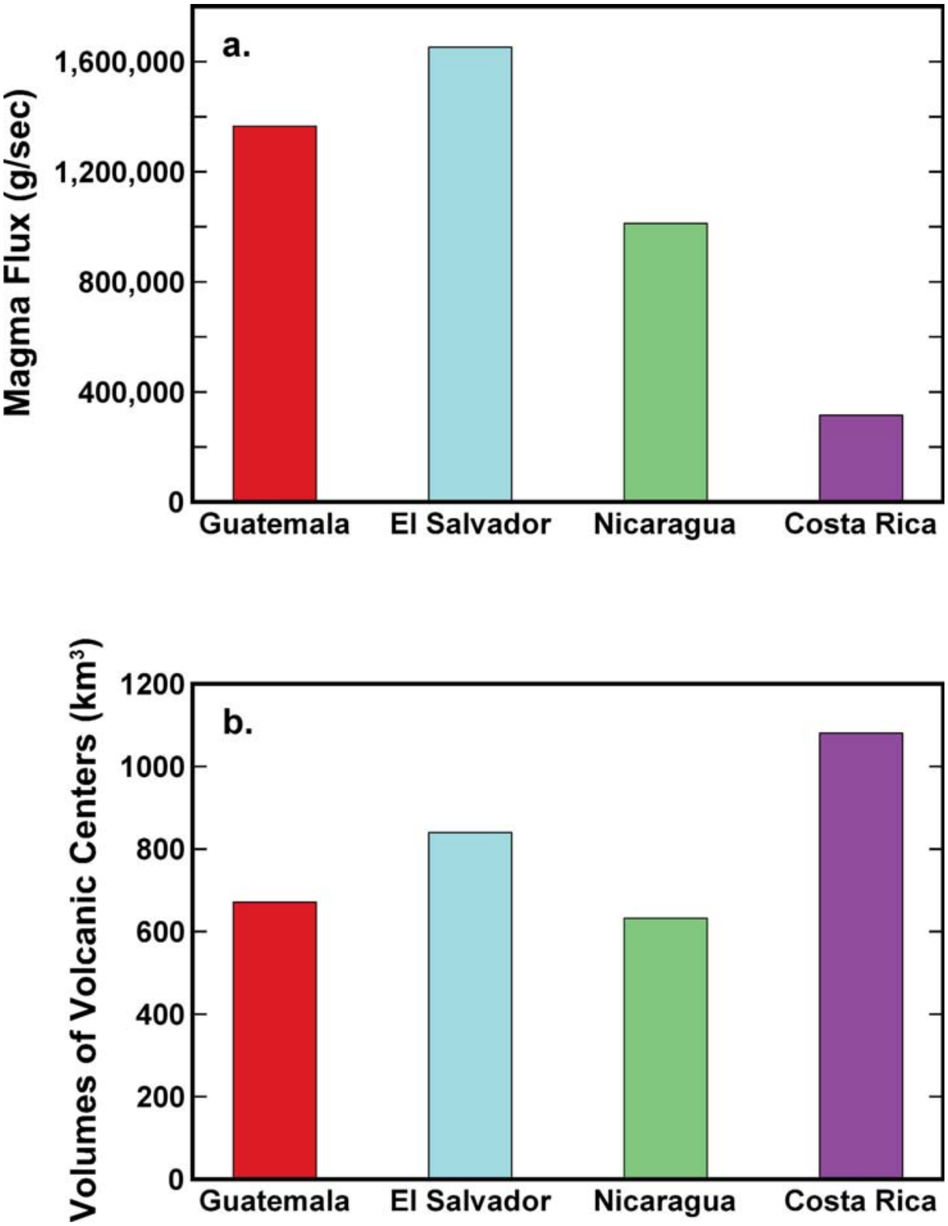

Figure 2. a. Estimates of magma flux in four portions of the Central American volcanic front from Kutterolf et al. (2008b). b. Estimates of the volumes of volcanic centers for same four portions of the Central American volcanic front from Bolge et al. (2009).

been regional in scope. Singer et al. (2011) instead focus on a single volcano – Santa María in Guatemala – and employ an extensive collection of ^{40}Ar/^{39}Ar age determinations, mostly from Escobar-Wolf et al. (2010). Their results indicate that this prototypical composite cone was constructed in four stages spanning approximately 75 kyr. The magma flux calculated by Singer et al. (2011) for building of the Santa María cone, based in part by energy-constrained recharge, assimilation, and fractional crystallization (EC–RAxFC) modeling (Bohrson and Spera 2007), is impressive – ca. 46 660 g/s, about 4 times the rate estimated by Kutterolf et al. (2008b). Moreover, Singer et al. (2011) point out that this magmatic input is also several times greater than those assumed in thermal models of the interaction between mantle-derived melts and the crust (Dufek and Bergantz 2005; Annen et al. 2006). Singer et al. (2011) also estimate a regional extrusion flux for Guatemala during cone construction at Santa María of 5–9 km^{3}km^{-1}Myr^{-1}, which is comparable to those reported by Carr et al. (2007a) for Nicaragua and Costa Rica.

NICARAGUA – WET INPUT AND OUTPUT?

Ranero et al. (2001) first report the occurrence of extensive bending-related faulting in the incoming Cocos Plate at the outer rise offshore Nicaragua. This structural control would lead to deep and widespread serpentinization of the mantle portion of the approaching plate, and hence an anomalously wet subduction input (Rüpke et al. 2002; Ranero et al. 2003). Subsequent geophysical investigations off Nicaragua lend support to this hypothesis (Grevemeyer et al. 2005, 2007; Ivandic et al. 2008, 2010; Lefeldt et al. 2009; Key et al. 2012). Grevemeyer et al. (2005) document lower than expected heat flow in the subducting Cocos Plate, which they attribute to enhanced hydrothermal circulation associated with bending-related faulting. A series of studies document slow seismic velocities in the outer rise offshore Nicaragua, suggesting 15–30% serpentinization of Cocos Plate mantle to at least a few kilometres below the Moho (Grevemeyer et al. 2007; Ivandic et al. 2008, 2010; Van Avendonk et al. 2011). Van Avendonk et al. (2011) estimate that the incoming Cocos slab is about 2.5 times wetter offshore Nicaragua versus offshore Costa Rica, and like all of the previous geophysical investigations, attribute this to widespread serpentinization of the mantle portion of the incoming Cocos Plate.

Onshore, Abers et al. (2003) find unusually slow seismic velocities at the top of subducting Cocos Plate beneath Nicaragua, suggesting an anomalously wet slab. In a more detailed study, Syracuse et al. (2008) also report anomalously low seismic velocities in the upper part of the subducting Cocos plate, extending 20–30 km below the slab surface, i.e. well into the mantle lithosphere. The observed velocity anomalies are consistent with 10–20% serpentinization of the subducting Cocos mantle. Therefore, compelling evidence exists on both sides of the trench for an uncommonly wet input into the Nicaraguan portion of the CASZ.

The consequences of this unusual hydrous influx have also been seismically imaged. In the Nicaraguan mantle wedge, Syracuse et al. (2008) distinguish a vertically extensive region having high ratios of primary to secondary wave velocities (V_P/V_S), thought to outline melt generated by the large water additions from the slab. Rychert et al. (2008), in a related investigation, show that the Nicaraguan mantle wedge exhibits a relatively wide zone of high shear wave attenuation that would indicate considerable wedge melting, hydration, excess temperatures, or some combination of all three. Hence, both studies provide convincing evidence for unusually large amounts of melting in the Nicaraguan mantle wedge that can be linked to an anomalously wet, serpentinized subducting plate.

There are a number of geochemical indicators that support the geophysical picture of an arc segment with enhanced melt production linked to an amplified delivery of water from the subducting Cocos plate. The first is that Nicaraguan mafic magmas and olivine-hosted melt inclusions define a regional minimum in La/Yb along the CASZ (Fig. 3a; Carr et al. 1990, 2003, 2007b; Sadofsky et al. 2008; Bolge et al. 2009). Carr et al. (1990, 2003, 2007b) attribute this to higher degrees of wedge melting which, in turn, implies a greater hydrous flux from the subducted slab, since flux-melting is generally thought to be the predominant means of magma production in subduction zones (Ringwood 1974; Ulmer 2001; Wallace 2005; Grove et al. 2012). Higher degrees of wedge melting in Nicaragua are also consistent with the lower Na_2O contents of mafic magmas and olivine-hosted melt inclusions erupted in Nicaragua compared with those emitted elsewhere along the CASZ (Carr 1984; Plank and Langmuir 1988; Eiler et al. 2005; Syracuse and Abers 2006; Carr et al. 2007b; Sadofsky et al. 2008). Sadofsky et al. (2008) conclude that (western) Nicaragua has a wetter mantle wedge and erupts somewhat wetter magmas than Guatemala and Costa Rica, based on water analyses of olivine-hosted melt inclusions (they had no data for El Salvador). Finally, Eiler et al. (2005) find that olivine phenocrysts from Nicaraguan lavas have unusually low δ^{18}O, both for the CASZ and for subduction zones worldwide (Fig. 3b). The Nicaraguan olivines also have anomalously low δ^{18}O relative to normal mid-ocean ridge basalts and mantle peridotites (Fig. 3b). These distinctively low values are ascribed to an aqueous fluid component from hydrothermally altered rocks deep within the subducting Cocos plate, possibly subducted serpentinites (Eiler et al. 2005). According to the modeling results of Eiler et al. (2005), this hydrous component has a much reduced to non-existent influence elsewhere along the CASZ.

Other geochemical proxies of water involvement in Nicaraguan magma genesis are more problematic or fail to single out Nicaraguan magmas. The first is the somewhat iconic regional peak in Ba/La exhibited by (western) Nicaraguan mafic lavas (Fig. 4a). Because a number of experimen-

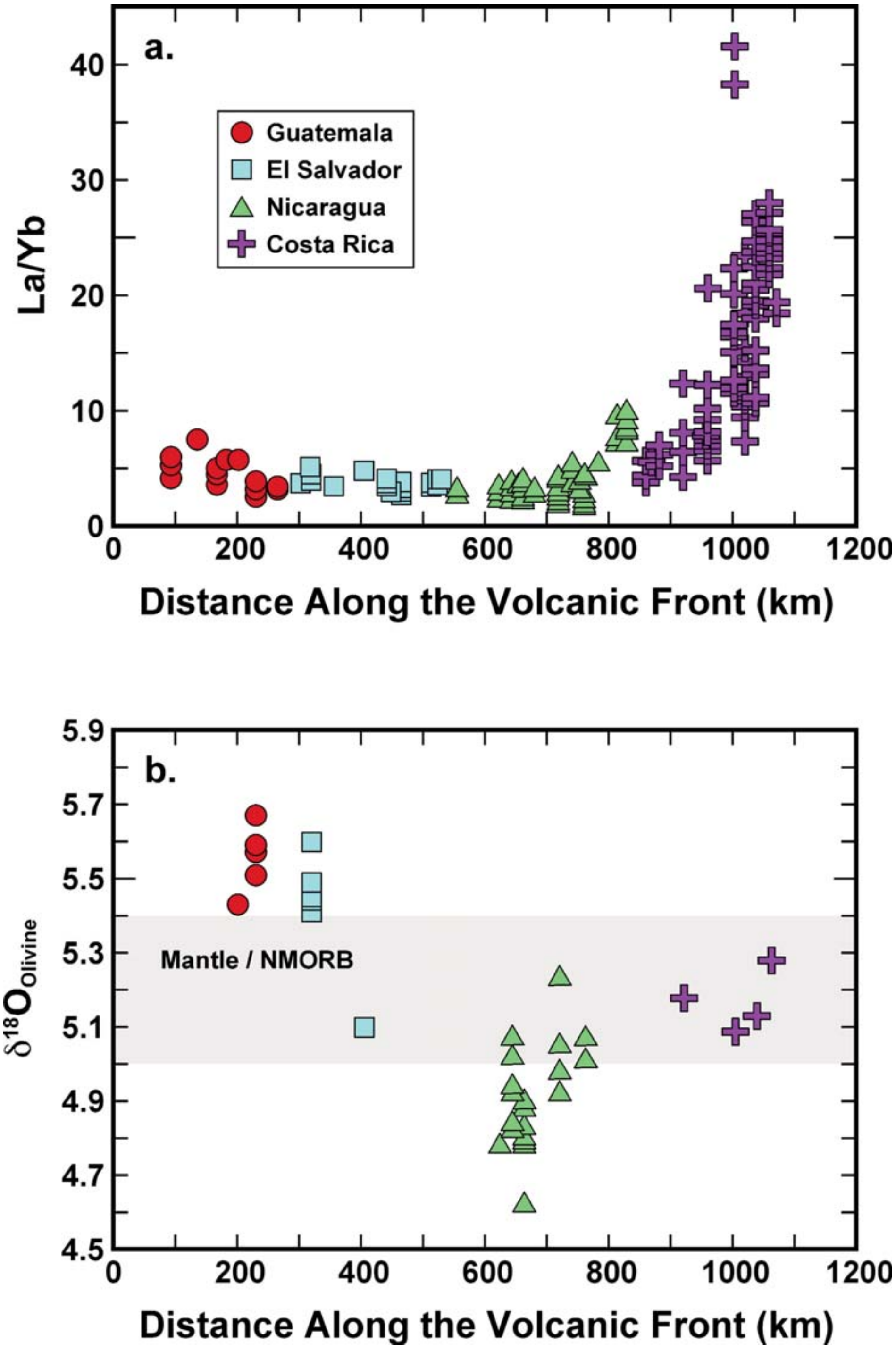

Figure 3. Variations of La/Yb (a) and δ^{18}O (b) in mafic volcanic rocks (45–55 wt% SiO$_2$) erupted along the Central American volcanic front. Data from RU_CAGeochem2013 database (http://rci.rutgers.edu/~carr/) supplemented with data from La Femina et al. (2004) and Singer et al. (2011). Shaded band represents δ^{18}O for most mantle peridotites and normal mid-ocean ridge basalts (Eiler et al. 2005).

tal studies have demonstrated that Ba is mobile during slab dehydration, whereas La is not (Tatsumi et al. 1986; Keppler 1996; Martin et al. 2011), Ba/La, like Ba/Nb and Ba/Th, is commonly employed as a proxy for a slab fluid component (Woodhead and Johnson 1993; Woodhead et al. 1998; Walker et al. 2000; Sadofsky et al. 2008; Bolge et al. 2009). However, the regional variation of Ba/La in mafic output in the CASZ actually reflects regional variability in La, not Ba (Carr et al. 1990, 2007a), as may be the case on a global scale (Morris and Hart 1983), and thus is more difficult to directly relate to a variable fluid flux. In addition, as first pointed out by Carr et al. (1990), and subsequently highlighted by others (Leeman et al. 1994; Jicha et al. 2010), the regional peak in Ba/La corresponds with a regional peak in a less ambiguous geochemical proxy, ^{10}Be (Fig. 4b). ^{10}Be is a clear tracer of the recycling of young subducting sediment (Tera et al. 1986; Morris et al. 1990), which in Central America would pinpoint source contributions from the upper sequence of hemipelagic sediments (Leeman et al. 1994; Patino et al. 2000). Since subducting sediments in the CASZ are distinctly enriched in Ba (Plank and Langmuir 1993; Leeman et al. 1994; Patino et al. 2000) and Ba/La (Patino et al. 2000), the Nicaraguan peak in Ba/La most likely reflects an increased slab signal from subducted (hemipelagic) sediments (Jicha et al. 2010). An enhanced flux from subducted (hemipelagic) sediments can also explain the along-arc peaks in B/La, U/Th, Ba/Th, and (^{230}Th/^{232}Th) seen in Nicaragua (Leeman et al. 1994; Patino et al. 2000; Carr et al. 2003; Walker et al. 2007; Sadofsky et al. 2008; Jicha et al. 2010). The He – CO$_2$ relationships and the δ^{15}N ratios of volcanic and geothermal fluids in Nicaragua also suggest elevated contributions from subducted sediments (Shaw et al. 2003; Elkins et al. 2006), although δ^{15}N ratios in Nicaragua are similar to those in Guatemala (Fischer et al. 2002; Elkins et al. 2006). Jicha et al. (2010) point out that ^{238}U excesses do not peak in Nicaragua, as might be expected if fluid input is maximized in this segment of the CASZ. Although ^{238}U excess is considered to be a robust indicator of the addition of U^{+6} as part of a fluid component from subducting lithosphere (Gill 1981; Allègre and Condomines 1982; Turner et al. 2003), it is a function of the fractionation of U from Th in aqueous fluids and not necessarily a measure of the overall water flux. The fact that ^{238}U excesses

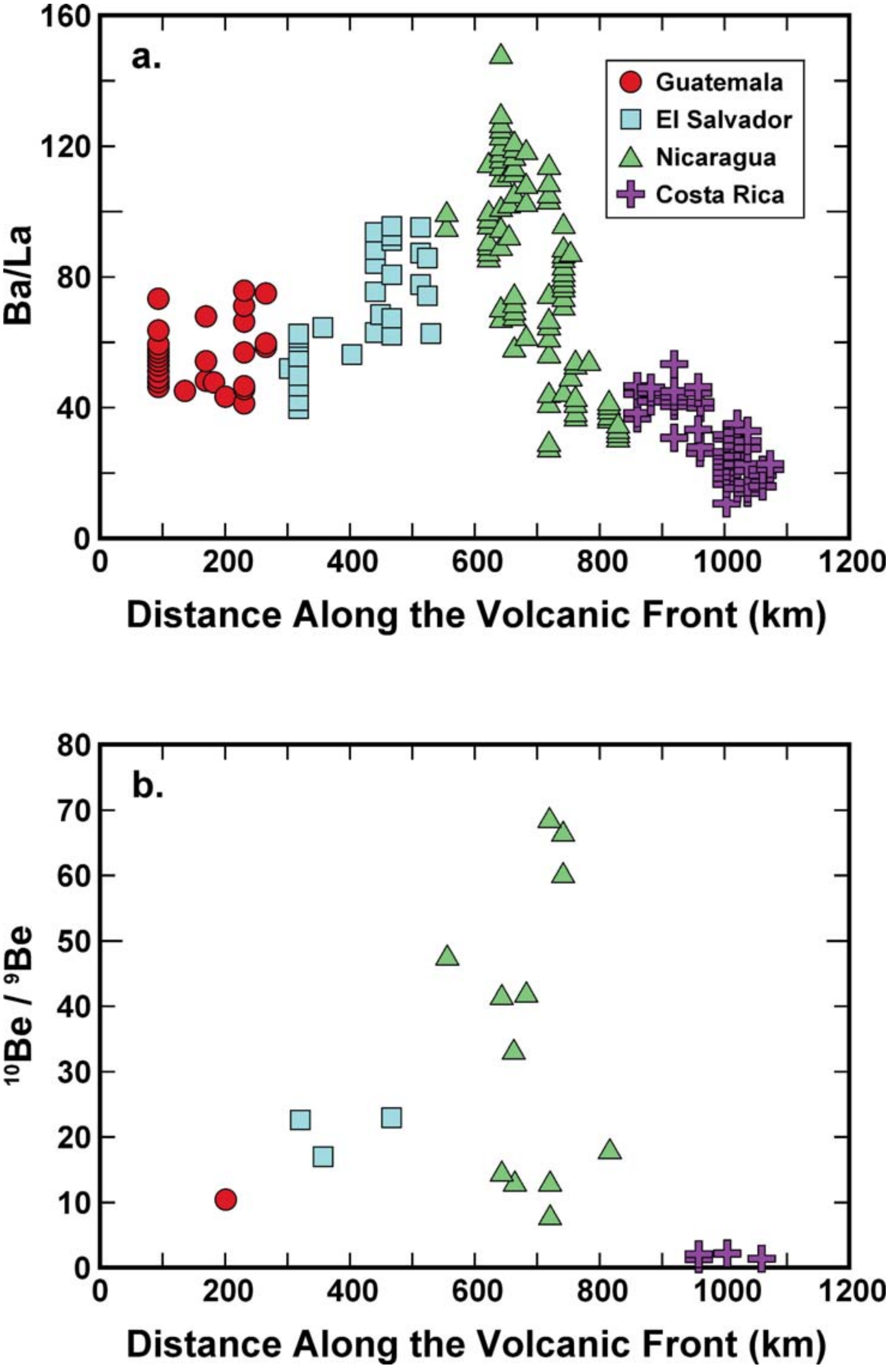

Figure 4. Variations of Ba/La (a) and ^{10}Be/^{9}Be (b) in mafic volcanic rocks (45–55 wt % SiO_2) erupted along the Central American volcanic front. Sources of data as in Figure 3.

extend from Guatemala to Costa Rica is, however, an important observation as it indicates that a fluid component of some sort is involved in magma genesis all along the CASZ.

An additional problem with the idea that wedge melting is maximized beneath the Nicaraguan portion of the CASZ is that, no matter the means of estimation, extrusive fluxes in Nicaragua do not stand out, as summarized above. In other words, the logical expectation is that with more melting there would be greater surface volcanism, particularly given that Nicaragua has the thinnest crust in the CASZ (Carr 1984; Carr et al. 1990, 2003). This discrepancy was first addressed by Carr et al. (1990), who attribute it to the steeper slab dip beneath Nicaragua. With a steep dip, water influx from the subducted Cocos plate is focused into a tighter volume, producing smaller quantities of high percentage partial melts that possess a more concentrated slab signal (Carr et al. 1990, 2003; Feigenson and Carr 1993).

We think a coupling of the models by Carr et al. (1990) and Eiler et al. (2005) best links the compelling evidence for an unusually wet input into the Nicaraguan segment of the CASZ and its equally distinctive volcanic output. The model of Carr et al. (1990) reconciles a regionally large degree of melting in the mantle wedge with a non-distinctive volcanic output. The enhanced degree of melting in Nicaragua is directly related to an anomalously wet input from the subducting Cocos plate, likely from serpentinites formed in the outer rise (Ranero et al. 2001, 2003; Rüpke et al. 2002; Eiler et al. 2005). In the model of Eiler et al. (2005), this wet addition is provided by their water-rich, low δ^{18}O component. As demonstrated by Eiler et al. (2005), a second slab component, required in Nicaragua to provide the necessary enhancements of ^{10}Be , Ba, B, U and other trace elements, must be subducted hemipelagic sediments (Morris et al. 1990; Plank and Langmuir 1993; Leeman et al. 1994; Patino et al. 2000; Rüpke et al. 2002; Shaw et al. 2003; Eiler et al. 2005; Elkins et al. 2006; Jicha et al. 2010). Eiler et al. (2005), following the current consensus (e.g. Elliott 2003), suggests that this second component is a sediment melt, although they provide it with very un-sedimentary Sr and Nd isotopic compositions. Leeman et al. (1994), on the other hand, favor addition of the sediment signal via fluid transport. The agent transporting the sedimentary component in Nicaragua remains an open question and may hinge on the relative mobilities of trace elements, particularly Be, Sr, Nd, and Hf, in various slab fluids (Tatsumi and

Isoyama 1988; You et al. 1994, 1996; Johnson and Plank 1999; Woodhead et al. 2001; Eiler et al. 2005; Marschall et al. 2007).

CENTRAL COSTA RICA – INPUT FROM THE GALAPAGOS PLUME

As shown in Figure 3a, volcanic rocks erupted in central Costa Rica have notably elevated La/Yb (Carr et al. 1990, 2003, 2007b; Herrstrom et al. 1995). Higher La/Yb implies a lower degree of partial melting or derivation from an enriched magma source. As shown in Figure 5, central Costa Rican volcanic rocks also have unusually enriched Pb isotopic compositions indicative of an enriched mantle source (Feigenson et al. 2004; Hoernle et al. 2008; Gazel et al. 2009, 2011). The overall correlation between La/Yb and Pb isotope ratios indicates that enriched magma sources are present where La/Yb is >10 (Gazel et al. 2009, 2011). The low Zr/Nb in central Costa Rican lavas is also supportive of an enriched mantle source (Bolge et al. 2009).

The observed source enrichment in central Costa Rica has been the subject of much debate. However, most studies have linked source enrichment to the influence of the Galapagos plume (Johnston and Thorkelson 1997; Abratis and Wörner 2001; Feigenson et al. 2004; Goss and Kay 2006; Hoernle et al. 2008; Gazel et al. 2009, 2011), which has had a fundamental role in the history of both the Caribbean and Cocos plates (Sinton et al. 1998; Werner et al. 1999, 2003; Hauff et al. 2000; Barckhausen et al. 2001; Hoernle et al. 2002; Denyer and Gazel 2009). Recall that the oceanic crust that subducts beneath central Costa Rica was formed at the Cocos – Nazca spreading center, and then overprinted by Galapagos hotspot tracks (Werner et al. 1999; O'Connor et al. 2007). In detail, the subducting Galapagos Seamount Province outboard of central Costa Rica has an alkaline composition and an isotopic signature of the Northern Galapagos Domain (Wolf – Darwin Lineament in the Galapagos Archipelago; Hoernle et al. 2000; Werner et al. 2003; Fig. 6). The subducting Cocos and Coiba ridges

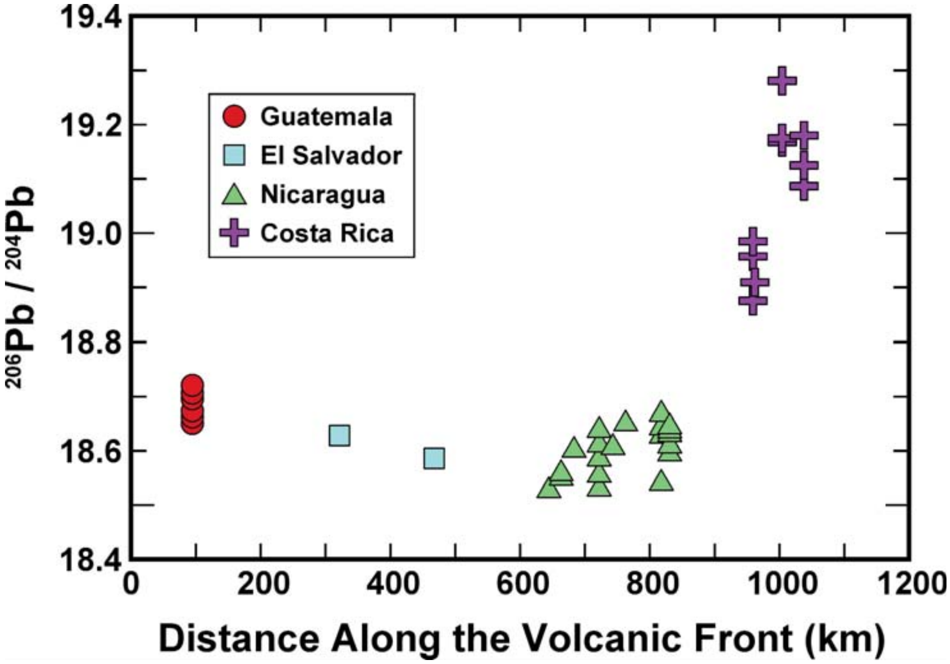

Figure 5. Variation of ^{206}Pb/^{204}Pb in mafic volcanic rocks (45–55 wt% SiO_2) erupted along the Central American volcanic front. Sources of data as in Figure 3.

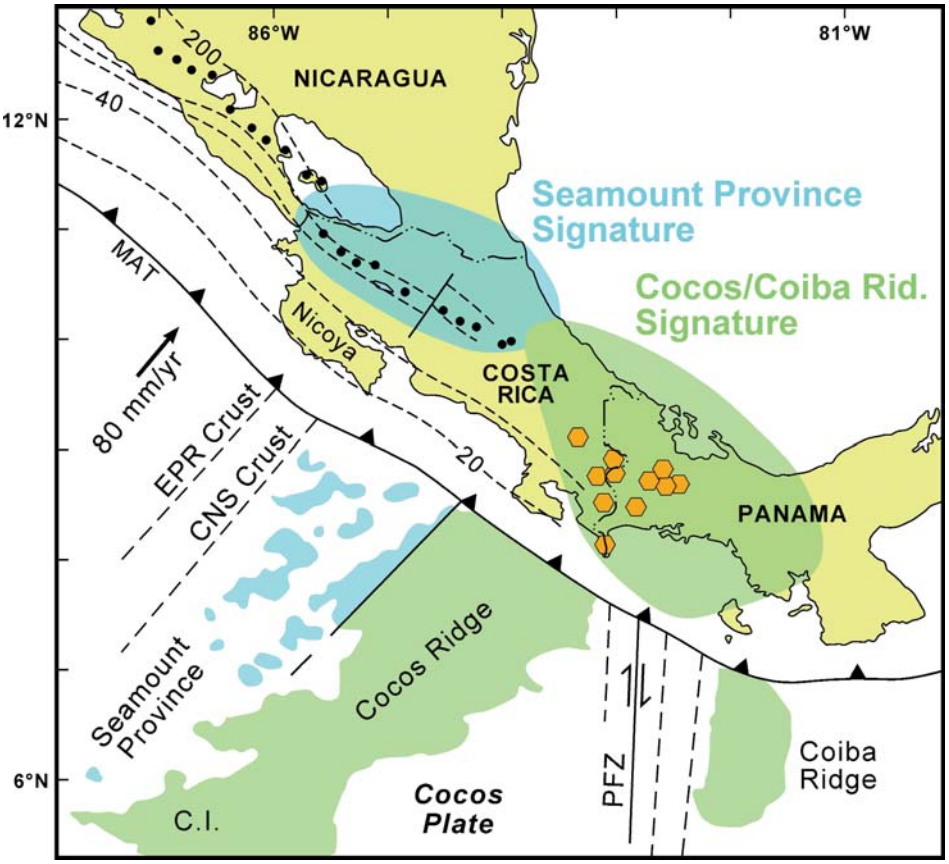

Figure 6. Tectonic setting of southern Central America (modified from Gazel et al. 2011). Black circles are volcanic complexes of the volcanic front. Orange hexagons are locations of adakitic volcanism. EPR: East Pacific Rise; CNS: Cocos-Nazca Spreading Center; C.I.: Cocos Island; PZF: Panama Fracture Zone. The depth contours of the subducting Cocos slab are from Protti et al. (1994).

have a tholeiitic composition with a dominant isotopic composition belonging to the central Galapagos Domain (Fernandina Island; Hoernle et al. 2000; Werner et al. 2003; Fig. 6).

The Pb isotopic compositions of samples from central Costa Rica can be explained by three isotopic end-members, a depleted component (depleted mantle) and two enriched subducting Galapagos components, the Seamount Province and the Cocos – Coiba Ridge (Fig. 7; Hoernle et al. 2008; Gazel et al. 2009). The Seamount Province is a recently arrived (<7 Ma) component; before that, the Galapagos interaction was dominated by a component similar to the Coiba and Cocos ridges that arrived at the subduction system ca. 15–10 Ma (Gazel et al. 2011). Based on radiogenic isotope systematics, geochemical variations with time, and geochemical modeling, Gazel et al. (2009) propose that the process to produce magmas with a Galapagos signature requires partial melting of subducting Galapagos tracks and reaction of those melts with the mantle wedge. These conclusions are in agreement with other recent studies (Benjamin et al. 2007; Hoernle et al. 2008) that provide convincing evidence that the anomalous enriched signature in the central Costa Rican portion of the volcanic front is derived from the interaction of the mantle wedge with Galapagos hotspot tracks. Hoernle et al. (2008) suggest that trench-parallel mantle flow, perhaps coupled with oblique subduction, causes diffusion of this Galapagos signature from central Costa Rica northwestward into Nicaragua. Trench-parallel mantle flow is consistent with recent seismic anisotropy data for the southern portion of the CASZ (Hoernle et al. 2008; Abt et al. 2009, 2010).

Gazel et al. (2009, 2011) show that the appearance of the Galapagos signature in the central Costa Rican volcanic front correlates with the production of magmas having primitive andesitic/adakitic compositions. Adakites are intermediate magmas produced by high-pressure melting of a mafic protolith, such as a subducted slab, and are recognized in part by their high La/Yb and Sr compositions (Kay 1978; Defant and Drummond 1990; Gazel et al. 2011; Whattam et al. 2012). Their presence in central Costa Rica strongly supports the occurrence of slab melting and its importance in explaining the enriched signature seen in southernmost CASZ magmas. Moreover, Gazel et al. (2011) report a migration of adakitic lavas of 35 mm/y towards the southeast, tracking the eastward movement of the triple junction where the Panama Fracture Zone intersects the Middle America Trench (Fig. 6). Seismic evidence (Protti et al. 1994) suggests that there is a slab ‘window’ beneath southern Costa Rica and Panama, in the area where adakites are common (orange hexagons in Fig. 6). The numerous hotspot tracks and fracture zones on the subducting Cocos and Nazca plates (Werner et al. 1999) could make the subducting slab below this part of the CASZ relatively easy to tear. Therefore, Gazel et al. (2011) hypothesize that a collision between the Galapagos hotspot tracks (Coiba Ridge?) and the CASZ that started ca. 15–10 Ma (Denyer and Arias 1991; Silver et al. 2004; MacMillan et al. 2004; Gazel et al. 2009) clogged the subduction zone and triggered slab detachment below southern Costa Rica and Panama. The detached slab segments were then replaced by hot asthenosphere, which is consistent with the elevated mantle potential temperatures (1400–1450 °C) in the mantle wedge below southern Central America (Gazel et al. 2011). The slab-free area correlates with the highest elevations (i.e. the Talamanca Cordillera at ca. 4 km) in southern Central America. These surface elevations are possibly related to the isostatic effect of the influx of hot mantle together with shortening related to the collision of the Cocos Ridge (Gazel et al. 2011).

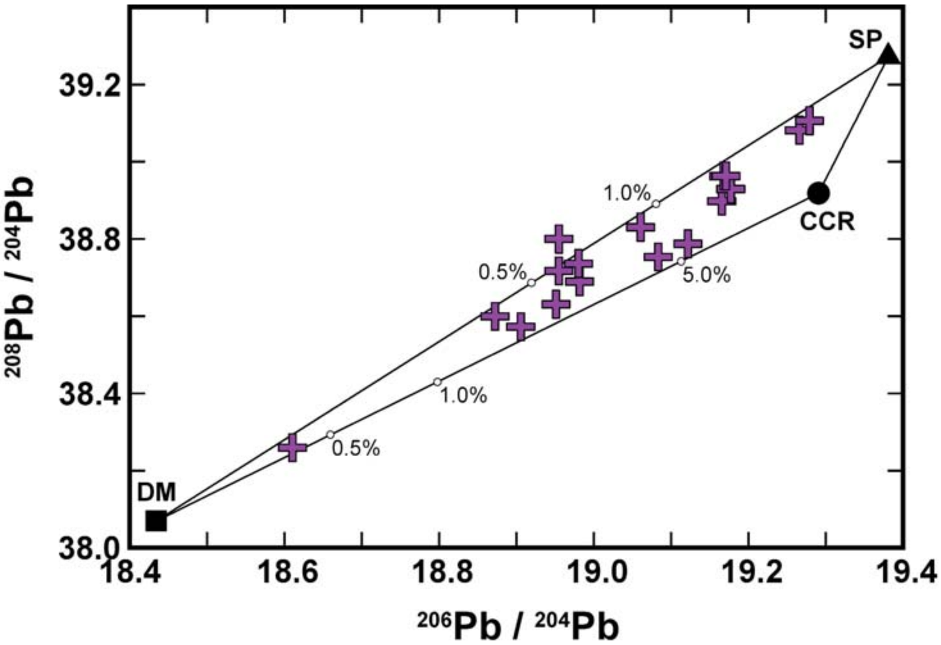

Figure 7. ^{208}Pb/^{204}Pb versus ^{206}Pb/^{204}Pb for Costa Rican lavas showing mixing lines from the three proposed source components: depleted mantle (DM), the subducting seamount province (SP), and the subducting Cocos – Coiba ridge (CCR). Sources of data as in Figure 3.

VOLCANIC SEGMENTATION AND HIGH-FIELD-STRENGTH-ELEMENTS

Stoiber and Carr (1973), Carr et al. (1982, 2007b), and Carr (1984), building on observations made by early explorers of Central America (Dollfus and Montserrat 1868; Sapper 1917), divided the Central American volcanic front into seven or eight segments, each from 100 to 300 km long, separated by changes of strike, ‘volcanic gaps’, or right-hand step-outs (Fig. 1). These along-front discontinuities are generally associated with transverse structures, such as faults and alignments of volcanic vents (Stoiber and Carr 1973). Although originally thought to reflect severance of both the overriding and subducting plates (Stoiber and Carr 1973; Carr et al. 1982), segmentation is now thought to be solely an upper plate phenomenon (Burkart and Self 1985; Bolge et al. 2009). Bolge et al. (2009) show that Zr/Nb correlates with the well-recognized segmentation of the Central American volcanic front; specifically, Zr/Nb in erupted, high-field-strength-element (HFSE)-depleted mafic magmas declines abruptly on the northwestern side of four proposed segment boundaries in El Salvador through Costa Rica (Fig. 8; Bolge et al. 2009). Bolge et al. (2009) demonstrate that these variations are controlled by changes in Nb, not Zr. All of the observed discontinuities in Zr/Nb correspond with right-hand steps in the volcanic front (Bolge et al. 2009). As a result, the variations in Zr/Nb are closely mimicked by sharp changes in slab depth, which abruptly decreases on the southeastern side of the segment boundaries, i.e. with each right-hand (trenchward) step (Fig. 1; Syracuse and Abers 2006; Bolge et al. 2009). Thus, at each right-hand step, slab depth decreases and Zr/Nb increases, caused by increasing Nb depletion in the erupted magmas (Bolge et al. 2009). It is important to point out that the discontinuous variations in Zr/Nb are superimposed on an overall along-arc trend in which western Nicaraguan lavas define a weak regional peak in Zr/Nb (Fig. 8; Bolge et al. 2009), grossly analogous to the along-arc variations in Ba/La and ^{10}Be (Fig. 4). Although not examined by Bolge et al. (2009), Hf/Ta variations in the CASZ are identical to Zr/Nb as is evident from the amazingly good correlation between the two incompatible element ratios (Fig. 9).

Bolge et al. (2009) speculate that the segmented Zr/Nb changes along the CASZ are controlled by variable amphibole stability during melting of the subducted Cocos plate. At shallower slab depths, residual amphibole is present during slab melting, resulting in high Zr/Nb if $^{\mathrm{Amph/L}}D_{\mathrm{Nb/Zr}}$ is >1 (e.g. Tiepolo et al. 2001). At greater slab depths, amphibole would not be stable during melting (e.g. Niida and Green 1999) resulting in low Zr/Nb (Bolge et al. 2009). Although amphibole control cannot presently be ruled out, we think rutile is a more likely option for directing relative HFSE fractionation along the CASZ. Rutile, unlike other possible accessory phases such as titanite, is well known for its ability to decouple

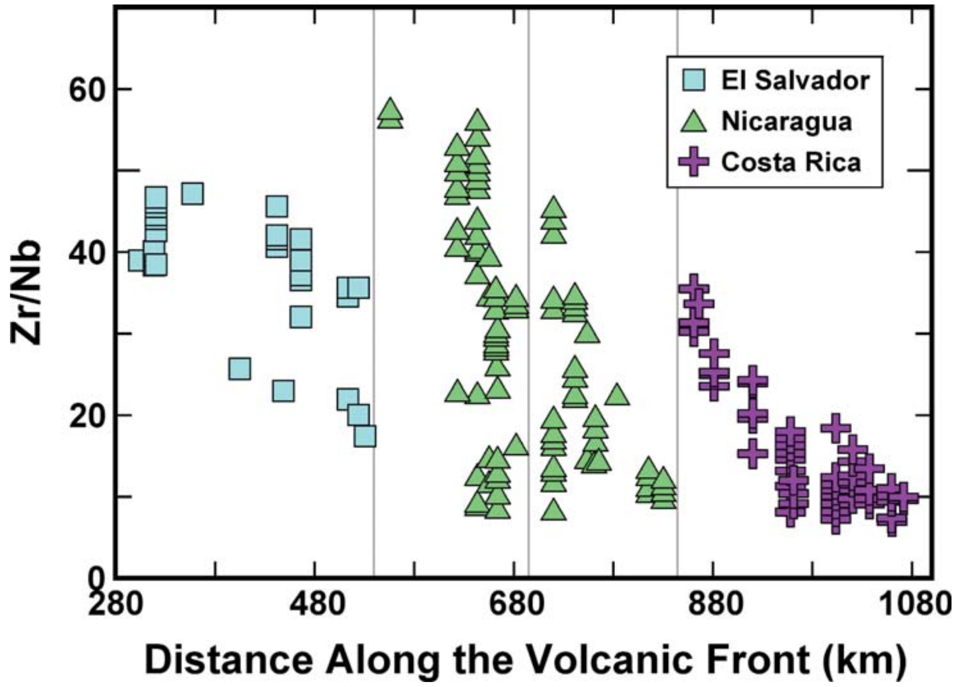

Figure 8. Variation of Zr/Nb in low-Ti mafic volcanic rocks (45–55 wt% SiO_2) erupted along the Central American volcanic front from El Salvador through central Costa Rica. Vertical lines show positions of proposed segment boundaries (see Fig. 1). Sources of data as in Figure 3.

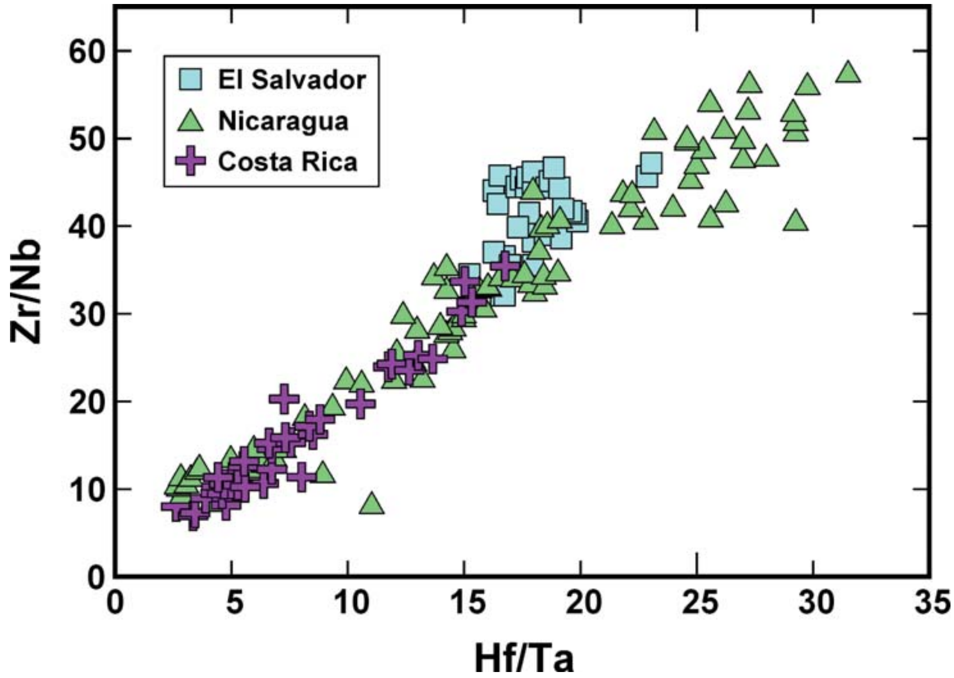

Figure 9. Zr/Nb versus Hf/Ta in low-Ti mafic volcanic rocks (45–55 wt% SiO_2) erupted along the Central American volcanic front from El Salvador through central Costa Rica. Sources of data as in Figure 3.

Nb and Ta from Zr and Hf (Jenner et al. 1993; Foley et al. 2000; Klemme et al. 2005; Xiong et al. 2005; Bromiley and Redfern 2008), which is the critical necessity along the CASZ. Rutile would also be a likely accessory phase in subducting siliceous sediments (Hermann and Spandler 2008; Skora and Blundy 2010) which, as discussed above, clearly exert a large influence on the trace element budget in Nicaragua and may do so further north along the CASZ as well. Bolge et al. (2009) dismissed rutile control for two reasons: first, because of its inability to explain a negative correlation between Zr/Nb and Nb/Ta; however, this negative correlation is seen only in El Salvador and there only moderately ($r^2 = 0.694$). Second, the stability of rutile is not pressure dependent; but pressure dependence is not essential, as the stability of the guiding mineral could be a stronger function of temperature, or in the case of partial melting, the degree of melting. For instance, at shallow slab depths and lower slab surface temperatures, rutile would likely be stable during melting or dehydration, resulting in high Zr/Nb and Hf/Ta. At higher temperatures, deeper along the slab surface, rutile might not be stable (Skora and Blundy 2010) or might become exhausted during melting, producing lower Zr/Nb and Hf/Ta in generated magmas.

SILICIC VOLCANISM – GENERATION OF JUVENILE CONTINENTAL CRUST?

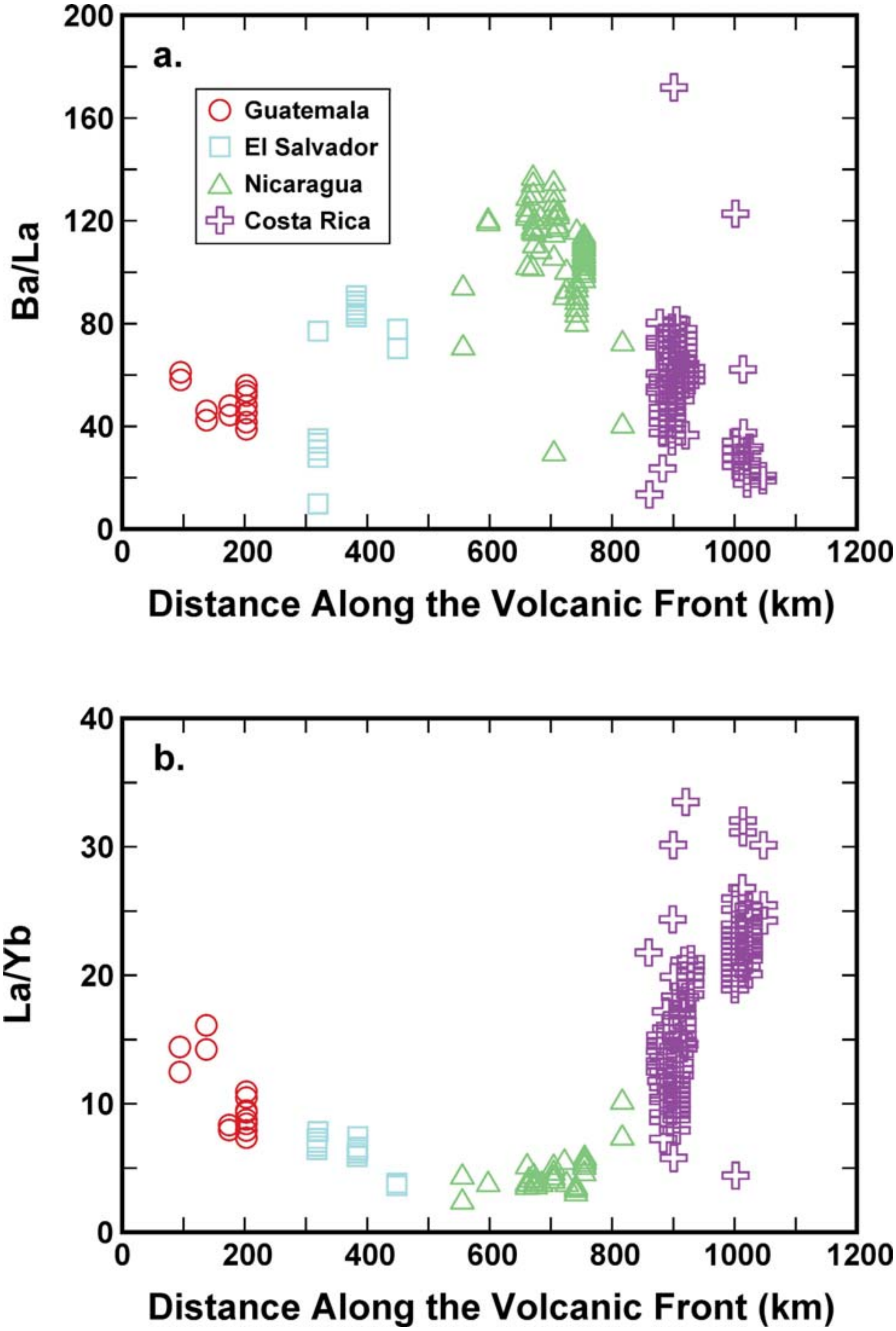

Figure 10. Variations in Ba/La (a) and La/Yb (b) in silicic volcanic rocks (65–77 wt% SiO_2) erupted along the Central American volcanic front. Data from Vogel et al. (2006) supplemented by data from Kutterolf et al. (2008a), Garrison et al. (2012), and the RU_CAGeochem2013 database.

Kutterolf et al. (2008b) have shown that silicic volcanism is volumetrically significant along the CASZ and may in fact dominate the overall magmatic output over the past few hundred thousand years. However, geochemical investigations of Central American silicic rocks are still too few and far between. One of the most important recent studies is that by Vogel et al. (2006), which expands on thoughts first presented in Vogel et al. (2004). In both papers, Vogel et al. (2004, 2006) stress that erupted felsic magmas along the Central American volcanic front display many of the same regional geochemical variations as their mafic brethren. For instance, the Ba/La ratios of silicic magmas, with two exceptions, peak in Nicaragua and fall off to the northwest and southeast (Fig. 10a). The regional pattern for La/Yb ratios, is, on the other hand, the almost mirror image of Ba/La, exhibiting a regional minimum in Nicaragua (Fig. 10b) – in fact, a more pronounced regional minimum than that shown by mafic magmas (Fig. 3a). In addition, the few available radiogenic isotopic compositions for silicic rocks overlap those of contiguous mafic rocks (Fig. 11). Thus, the silicic magmas of Central America seem to have had little, if any, crustal inheritance, no matter the thickness or com-

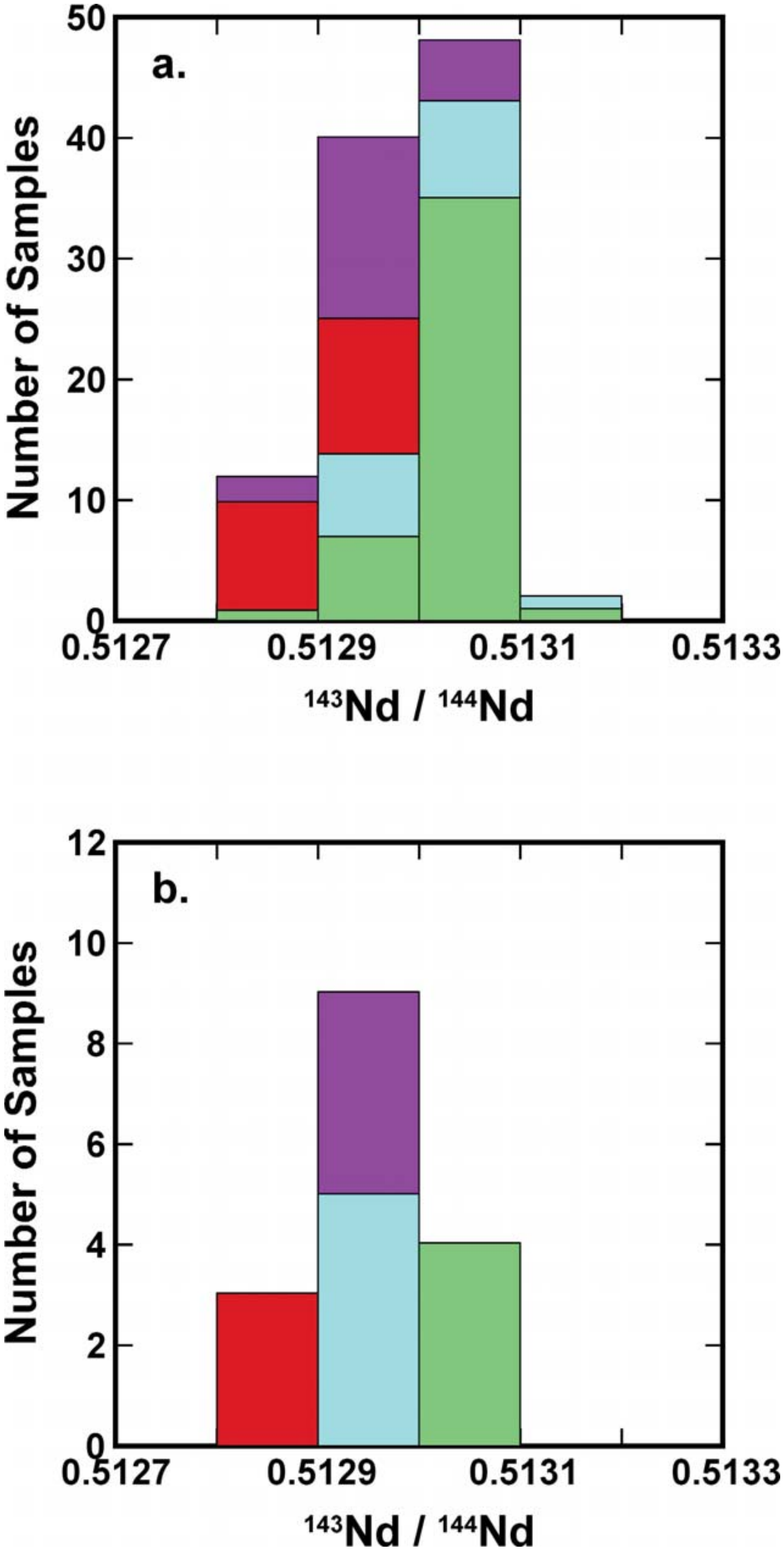

Figure 11. Nd isotopic compositions of mafic (a) and silicic (b) volcanic rocks (as delineated in previous figures) erupted along the Central American volcanic front. Colour distinctions as in previous diagrams, i.e. red – Guatemala, blue – El Salvador, green – Nicaragua, and purple – Costa Rica. Data from RU_CAGeochem2013 database, Vogel et al. (2006), Singer et al. (2011), and Garrison et al. (2012).

position of crust they inhabited and traversed (Vogel et al. 2006). This would suggest that juvenile continental crust is being created all along the CASZ (Vogel et al. 2004; Deering et al. 2012). The preferred model of Vogel et al. (2006) for the origin of Central American silicic magmas is by penecontemporaneous partial melting of recently crystallized mafic intrusions (Tamura and Tatsumi 2002), or by melt extraction from more mafic crystal mushes (Deering et al. 2012).

Nevertheless, partial melting of subducting lithosphere may also play a significant role in the generation of continental crust (Drummond and Defant 1990; Rapp and Watson 1995; Hacker et al. 2011). This process would be facilitated if the slab were enriched in incompatible-elements by plume interaction as in the case of Costa Rica (Gazel et al. 2009, 2011). Partial melting of subducting hotspot tracks can 're-fertilize' the arc mantle wedge. Once the enriched starting material is produced, intra-crustal processes such as fractional crystallization, assimilation and anatexis (e.g. Hildreth and Moorbath 1988; Annen et al. 2006) will complete the development of juvenile continental crust. This process, which may be occurring on a large scale in Costa Rica, is consistent with a recent geophysical study (Hayes et al. 2013) showing that Costa Rica has average *P*-wave velocities that are closest to continental crust of any non-continental subduction zone, worldwide.

DIRECTIONS AND QUESTIONS FOR THE FUTURE

A number of important avenues for future research in the CASZ fall out of this review. The first is further applications of high-precision ^{40}Ar/^{39}Ar dating to individual volcanoes in order to better constrain extrusive and magmatic fluxes along the CASZ (e.g. Singer et al. 2011). A second is to examine whether the sediment signature seen in Nicaraguan volcanic rocks is delivered by a fluid or a melt from the subducting Cocos plate. Acquisition of Hf isotopic data could shed light on this question, depending on whether the Hf isotopic composition of the CASZ mantle wedge is distinct from that of the subducting Cocos crust (Tollstrup et al. 2010). Definitive geochemical evidence of a serpentinite-derived component in Nicaragua is also lacking: chlorine isotope values for volcanic rocks, like those of oxygen isotopes, are only suggestive of a serpenitinite signature (Barnes et al. 2009). Tonarini et al. (2007) utilize B isotopes to argue for fluid inputs in El Salvador; a similar B isotopic study of Nicaraguan volcanic rocks is needed to validate the approach of Tonarini et al. (2007) in the segment of the CASZ with, at present, the strongest geophysical evidence for serpentinite subduction (e.g. Van Avendonk et al. 2011) and the most robust geochemical evidence for a wet slab input. Another important research question is the character of fluid addition from the subducting Cocos plate in portions of the CASZ away from Nicaragua, as U–series data suggest fluid involvement all along the CASZ, even in Costa Rica (Benjamin et al. 2007; Jicha et al. 2010). Future investigations of HFSE variability along the Central American volcanic front are also vital to identify which minor or accessory phases (or phase) control(s) the observed variation and how it relates to CASZ segmentation and slab depth (Bolge et al. 2009). One aspect of HFSE variability not discussed in this review is the occurrence of unusual HFSE-enriched volcanic rocks along the volcanic front, particularly in Nicaragua and Costa Rica (Ui 1972; Walker 1984; Reagan and Gill 1989; Walker et al. 1990, 2001; Alvarado and Carr 1993; Feigenson and Carr 1993; Reagan et al. 1994; Patino et al. 2000; Carr et al. 2003, 2007b; Sadofsky et al. 2008; Freundt et al. 2010; Rausch and Schmincke 2010). The origin of these atypical volcanic rocks is still controversial and wants further study, bearing in mind that the Nicaraguan and Costa Rican examples are geochemically quite distinct (Walker et al. 1990, 2001). Another research focus for the CASZ in the future should be the origin and evolution of silicic volcanism, particularly within large caldera systems. The Vogel et al. (2006) hypothesis of important juvenile crustal production all along the volcanic front requires geochemical testing, especially with radiogenic isotope data. Last, and perhaps most important, both onshore and offshore geophysical studies of northern Central America are imperative. These would provide an important foundation for vital assessments of the geochemical variations along the northern half of the Central American volcanic front, which are sometimes as robust as those in the southern half (Figs. 3b and 4), but have attracted scant scientific attention. Readers interested in examining the geochemistry of CASZ volcanic rocks further are encouraged to download the RU_CAGeochem database from http://rci.rutgers.edu/~carr/.

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