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Key Points:
- The Talamanca Cordillera preserves the record of the evolution from an intra-oceanic arc to a juvenile continental
- Plutonic rocks from this transition and post-intrusive rocks share striking similarities with average upper continental crust and TTG
- Seismic velocity profiles suggest a transition towards more felsic compositions as the volcanic axis migrated

Supporting Information:
- Table S1
- Table S2
- Table S3

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The Record of the Transition From an Oceanic Arc to a Young Continent in the Talamanca Cordillera

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Abstract The Talamanca Cordillera in the Central America Arc (Costa Rica-Panama) preserves the record of the geochemical evolution from an intraoceanic arc to a juvenile continental arc in an active subduction zone, making it a testbed to explore processes that resulted in juvenile continental crust formation and explore potential mechanisms of early continental crust generation. Here we present a comprehensive set of geochronological, geochemical, and petrological data from the Talamanca Cordillera that tracks the key turning point (12–8 Ma) from the evolution of an oceanic arc depleted in incompatible elements to a juvenile continent. Most plutonic rocks from this transition and postintrusive rocks share striking similarities with average upper continental crust and Archean tonalite, trondhjemite, and granodiorite. We complement these data with seismic studies across the arc. Seismic velocities within the Caribbean Plate (basement of the arc) show a relatively uniform lateral structure consistent with a thick mafic large igneous province. Comparisons of seismic velocity profiles in the middle and lower crust beneath the active arc and remnant Miocene arc suggest a transition toward more felsic compositions as the volcanic center migrated toward the location of the modern arc. Seismic velocities along the modern arc in Costa Rica compared with other active arcs and average continental crust suggest an intermediate composition beneath the active arc in Costa Rica closer to average crust. Our geochemical modeling and radiogenic isotopes systematics suggest that input components from melting of the subducting Galapagos hotspot tracks are required for this compositional change.

1. Introduction

Earth's crust is the life-sustaining interface between the planet's deep interior and surface. Most "terrestrial" planets have basaltic crusts similar to Earth's oceanic crust, which is produced by decompression melting of the upper mantle. Within the solar system, Earth is unique in having continental regions of buoyant, thick, silicic crust (Rudnick & Gao, 2003; Taylor & McLennan, 1995). Understanding the processes responsible for the formation of continents is fundamental to reconstructing the evolution of our habitable planet. Although there is evidence for the existence of a protocontinental crust as early as 4.5 Ga recorded in detrital zircons found in Western Australia (Harrison et al., 2008; Valley et al., 2014), geochemical evidence and petrologic modeling suggest the peak of cratonization (i.e., the stabilization of most continental masses) occurred in the Archean between ~3.5 and 2.5 Ga (Carlson et al., 2005; Hawkesworth & Kemp, 2006; Herzberg & Rudnick, 2012; Patchett & Arndt, 1986; Taylor & McLennan, 1995). Thus, fundamental questions in the evolution of our planet that still need to be answer are as follows: Whether new or "juvenile" continental crust is actively forming in the modern tectonic regime? Where the roots of all continental masses established in the Archean (or earlier) and if the planet has been in steady state recycling of crustal material since then?

Two competing models that provide explanation for the formation of continental crust in early Earth: the stagnant lid model and the subduction model. The stagnant lid model suggests that during the early part of Earth's evolution the crust behaved as a rigid, slowly creeping lid overlying an actively convective mantle. Delamination of dense eclogite into the less dense asthenosphere at the base of the lithosphere resulted in upwelling of hotter asthenosphere that subsequently decompressed to generate melt (e.g., Condie et al., 2011; van Thienen et al., 2004; Van Kranendonk, 2010; Zegers & van Keken, 2001). The foundering of denser material would have enhanced decompression melting and catalyzed multiple melting events that

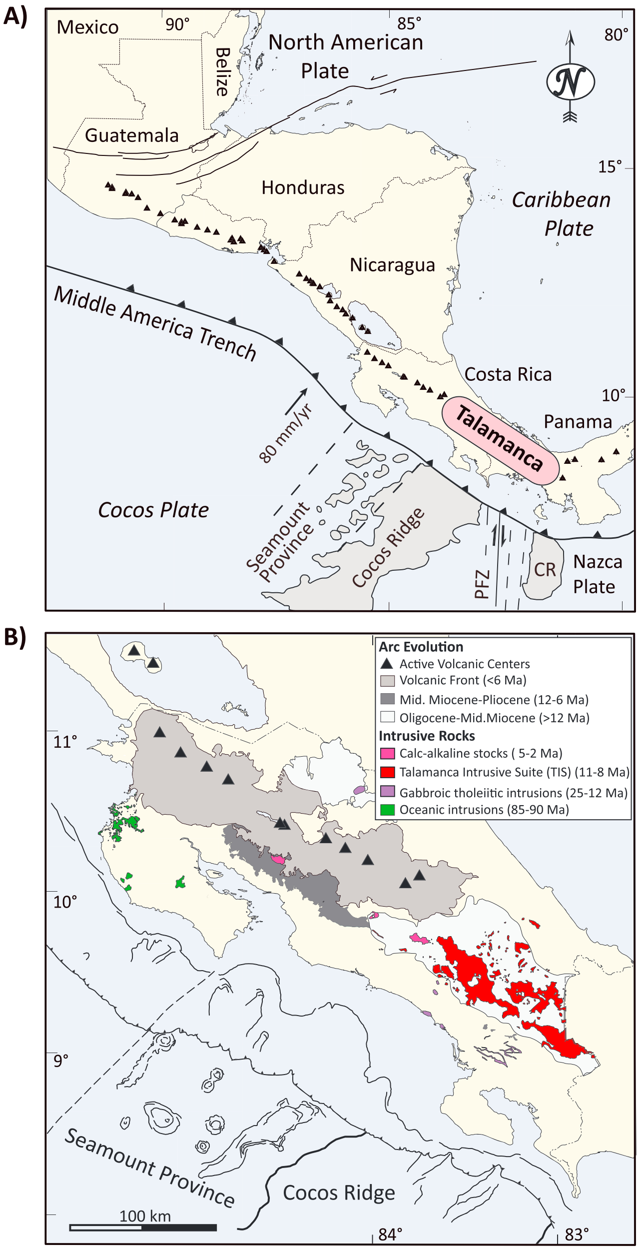

Figure 1. Location of the study area. (a) Tectonic configuration: The Cocos Plate subducts beneath the Caribbean Plate toward the northeast at an average velocity of 80 mm/year along the Middle America Trench, generating the Central America Volcanic Arc (active volcanoes as black triangles) from Guatemala in the northwest to Panama in the southeast. Galapagos Plume tracks that includes the Costa Rica Seamount Province, the Cocos Ridge, and the Coiba Ridge (CR), are subducting in front of the Talamanca Cordillera. PFZ: Panama Fracture Zone. (b) Volcanic Arc evolution record in Costa Rica: Note that the northwestern section of the arc exposes extrusive volcanic units since the Mid-Miocene-Pliocene, the southeastern section (the Talamanca Cordillera) preserves mostly Miocene intrusive rocks (Alvarado & Gans, 2012; Denyer & Alvarado, 2007; Gazel et al., 2009; Whattam, 2018).

ultimately generated suites of tonalite, trondhjemite, and granodiorite (TTGs) that rose to Earth's surface to form felsic continental crust (Bédard, 2006; Johnson et al., 2014; Smithies et al., 2009). Although the “stagnant lid” model is numerically plausible, melting an anhydrous basaltic protolith produces small melt fractions that differ in composition from Archean TTGs (Moyen & Stevens, 2006). Additionally, the nearly ubiquitous occurrence of hydrous phases (e.g., amphibole and biotite) in most granites and the high-T solidus of dry basalt, suggests that the source material contained water; thus water is needed to generate large volumes of granitic melts found at cratonic locations (Arndt, 2013; Foley et al., 2002; Martin et al., 2005). Finally, the lack of continental crust on other terrestrial planets with stagnant lid regimes like Mars, Venus, and Earth's Moon (e.g., McSween et al., 2003) suggest the need of additional processes to produce the continental crust unique to Earth. Recent in situ rover measurements suggest the possibility that pockets of felsic material discovered in Mars can be the remnants of ancient continental crust (Sautter et al., 2015). However, petrologic modeling and statistical comparisons imply that these felsic rocks are likely the result of fractional crystallization of intraplate magmas, and thus, early continental crust production in Mars can be ruled out (Udry et al., 2018).

In contrast, subduction models call on a more uniformitarian perspective for continental crust formation and suggest that modern-style plate tectonics operated in the Hadean-Archean, despite higher mantle temperatures and complex internal planetary dynamics (Herzberg et al., 2010; Korenaga, 2006). Subduction processes would account for the H_2O needed for the melting of the subducting slab and explains the geochemical similarities between TTG and modern slab melts (Arndt, 2013; Martin et al., 2005; Moyen & Stevens, 2006). In this model, hotter mantle potential temperatures and a steeper geothermal gradient across the subducting slab zone resulted in slab melting prior to the breakdown of hydrous minerals. This process accounts for the high melt fractions needed to produce thick continental crust. The even thicker and buoyant residual lithospheric mantle probably made subduction processes sluggish (van Hunen & Moyen, 2012, and references therein) but feasible and episodic (Debaille et al., 2013; Griffin et al., 2014; Rey et al., 2014).

Given the plausible conditions under which early continental crust formed, analyzing modern analogues can provide a better understanding of the processes responsible for the formation of continental crust. Intraoceanic arcs provide modern analogues for the “subduction model” of new continental crust, in this case both subducting and overriding plates have an oceanic origin (Rudnick & Gao, 2003). However, their use as analogues for continental crust generation is controversial due to the fact that seismic studies of island arcs suggest that they are generally dominated by basaltic compositions (Calvert, 2011; Fliedner & Klemperer, 2000; Gazel et al., 2015; Holbrook et al., 1999; Shillington et al., 2004) and where andesitic melts are produced, they are generally depleted in incompatible elements compared to average continental crust estimates (Gazel et al., 2015; Kelemen, 1995; Kelemen, Hanghj, et al., 2003; Kelemen, Yogodzinski, et al., 2003).

Therefore, in order to elucidate the processes that produce juvenile continental crust in subduction systems, focus must be directed toward arcs where the volcanic output resembles juvenile continental crust produced in the Archean. This arc crust must represent an average upper continental crust composition that also

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includes erupted material that is geochemically similar to Archean TTGs. On the basis of the correlation between average V_P and a continental index used to compare the chemical composition of magmas produced to global continental crust estimates (Gazel et al., 2015), one of the best locations to study the production of juvenile continental crust is along the Central American Land Bridge (Costa Rica and Panama, Figure 1). The results presented hereafter focus on the magmatic record of the Talamanca Cordillera located at the core of the Central American Land Bridge. This cordillera is an uplifted region (up to ~4 km above sea level) in a 195-km gap between active volcanic systems: Irazu-Turrialba volcanic complex in Costa Rica and Baru volcano in Panama (Carr et al., 2007; Sak et al., 2009). We present a comprehensive set of geochronological, geochemical, and petrological data from the Talamanca Cordillera that tracks the key turning point from the evolution of an oceanic arc depleted in incompatible elements to a juvenile continental mass focusing on the intrusive record in order to evaluate current models of continental crust formation based on the evolution of this natural laboratory. These data are supported by geochemical modeling using different subducting components to test the hypothesis presented here. We also provide complementary 1-D V_p profiles in representative areas of the arc (Caribbean Plate, Miocene arc, and Modern Volcanic Front) to examine the deep composition and its relation with the record geochemical changes in the arc.

2. Tectonic Setting

The active Central American Volcanic Front extends parallel to the Middle American Trench from the Mexico-Guatemala border to western Panama (Figure 1). The convergence rate between the Cocos and Caribbean plates increases toward the southeast from ~60 mm/year off southern Guatemala to ~90 mm/year off southern Costa Rica (DeMets, 2001). Oceanic crust of >17 Ma produced at the East Pacific Rise spreading center readily subducts along the margin to the north of Costa Rica (Ranero & von Huene, 2000; Ranero et al., 2003; Figure 1). In contrast to crust originating at the East Pacific Rise, oceanic crust subducting from Central Costa Rica northward to the Panama border was produced at the Cocos-Nazca spreading center and is overprinted by the Galapagos hotspot tracks, 13.0–14.5 Ma (Werner et al., 1999; Figure 1). Subduction of these Galapagos tracks is active in the Middle American Trench, as seismic evidence suggests that the Cocos Ridge and the associated seamount provinces can be traced to at least 80 km below the volcanic arc and the Talamanca Cordillera (Arroyo et al., 2009; Dinc et al., 2010).

The volcanic front in the Central American Land Bridge developed over oceanic crust on the western edge of the Caribbean Plateau, a thick oceanic plate without any preexisting continental material (Dengo, 1985; Denyer & Gazel, 2009; Hauff et al., 2000; Pindell et al., 2006; Whattam et al., 2016). Geochemical variations of trace elements and Pb, Sr, Nd, and O isotopes along the volcanic front of Central America are similar in both silicic (SiO_2 > 65wt%) and mafic lavas (Feigenson et al., 2004; Gazel et al., 2011; Vogel et al., 2004). This suggests that the silicic magmas are genetically related to the basaltic magmas that were produced in the mantle wedge. The O-isotope variations suggest limited hydrothermal alteration, supporting the conclusion that assimilation of altered volcanic rocks was not a major process in the production of these silicic melts (Vogel et al., 2006). Along the volcanic front in Central America only the Guatemalan lavas clearly show the effects of crustal contamination or interaction with old lithosphere (Feigenson et al., 2004; Heydolph et al., 2012). Thus, preexisting continental crust can be ruled out as a possible source for southern Central America (Costa Rica-Panama) magmas (Gazel et al., 2015).

Pichler and Weyl (1975) were the first to suggest that intraoceanic arc crust in Costa Rica has been gradually transformed to a young continent by the emplacement of silicic magmas. This idea was explored by Vogel et al. (2004), who proposed that addition of silicic magmas to the crust of Costa Rica led to the conversion of this crust to a more continental character over time. Drummond et al. (1995) suggested that the Talamanca Cordillera possibly provide the key record of this evolution. Gazel et al. (2009, 2015) presented a geochemical reconstruction of the arc that clearly demonstrated the evolution from geochemical compositions depleted in incompatible elements dominated by magmas with basaltic compositions in the Cretaceous-Middle Miocene (similar to modern Nicaragua and Marianas volcanic front lavas) to andesitic compositions in the Late Miocene to present (more similar to continental crust). This evolution was interpreted to be the result of the most recent interaction with the Galapagos tracks starting ~12 Ma ago. This interaction resulted in a collision and oblique subduction (12–5 Ma; MacMillan et al., 2004) coeval with the emplacement of intrusive series in the Talamanca Cordillera (~11–8 Ma). These plutonic rocks

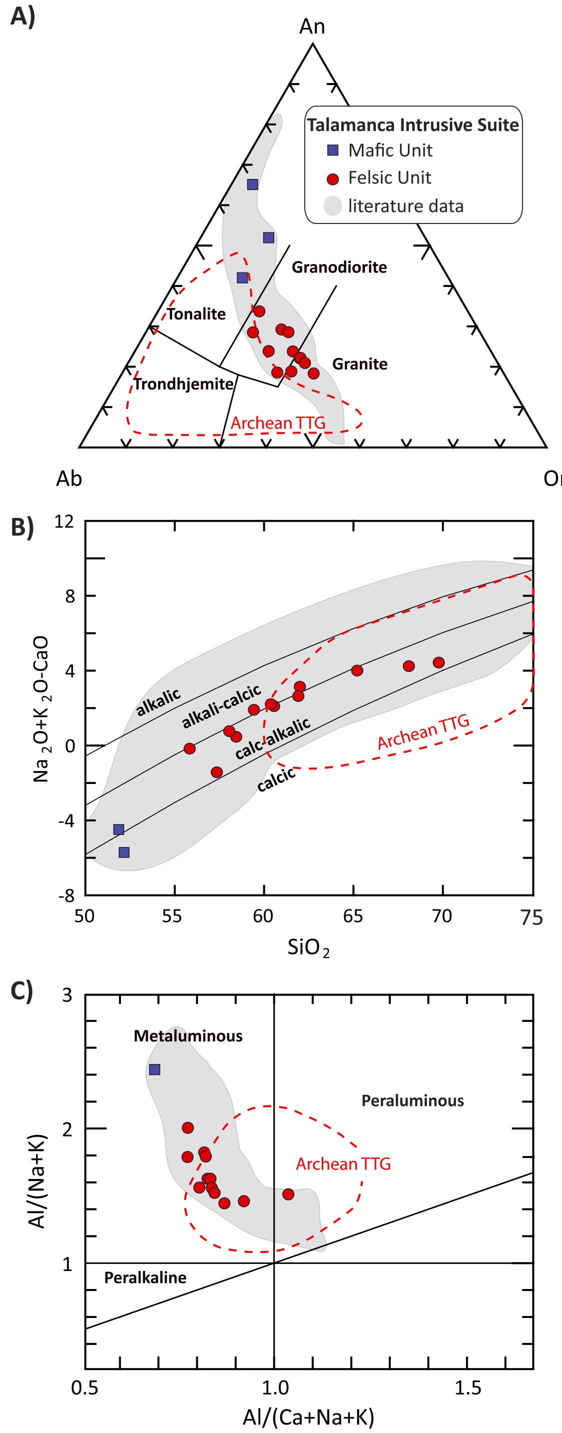

Figure 2. Geochemical diagrams for the intrusive rocks of the Talamanca Intrusive Suite. (a) The An-Ab-Or diagram (Barker, 1979). (b) Magmatic series (Frost et al., 2001) showing that the mafic suite tends to be calcic to calc-alkalic and the felsic suite calc-alkalic to alkali-calcic. (c) Shand index (Maniar & Piccoli, 1989) showing the metaluminous domain of the Talamanca Intrusive Suite, the granophyres and the alkali granites are slightly peraluminous. Additional data (gray shadow) compiled from Tournon (1984), Drummond et al. (1995), Gräfe (1998), and Abratis (1998). The dashed line represents the range of Archean tonalite, trondhjemite, and granodiorite (TTG) from Moyen (2011).

crystallized at a depth of ~5 km and constitute a record of the development of the arc during the Late Miocene-Pliocene (Abratis, 1998; De Boer et al., 1995; Drummond et al., 1995; Gazel et al., 2009; MacMillan et al., 2004).

Subsequent volcanic activity in the Talamanca Cordillera is represented by primitive andesite/adakitic-like suites (<5 Ma) exposed as individual domes in the central part of the cordillera and near the Panamanian-Costa Rican border (Abratis & Wörner, 2001; Defant et al., 1992; Gazel et al., 2011; MacMillan et al., 2004). Gazel et al. (2011) reported on the migration of primitive andesites/adakites at 35 mm/year from northwest to southeast, tracking the eastward movement of the triple junction where the Panama Fracture Zone intersects the Middle America Trench. These primitive andesites have mantle-like oxygen isotopes and a clear Galapagos geochemical signature that suggest reaction of slab-derived melts with the mantle wedge (Bindeman et al., 2005; Gazel et al., 2009; Gazel et al., 2011; Hoernle et al., 2008).

In this study, we focus on the key transition from an oceanic arc to the early stages of a continental arc recorded in the magmas from the Talamanca Cordillera (Late Miocene-Pliocene) that in most of the region has been lost to erosion or was covered by more recent volcanic events. Our goal is to test the subduction model as a possible explanation of early continental crust production on Earth.

3. Materials and Methods

In addition to creating detailed geologic maps, we collected samples of preintrusive, intrusive, and postintrusive magmatic rocks from the Talamanca Cordillera. All samples have been previously described by petrographic studies and characterized by electron microprobe (Ulloa-Carmiol & Delgado-Segura, 2009). On the basis of petrographic and mineral chemistry studies, five key samples were dated by step heating $^{40}Ar/^{39}Ar$ to complement the existing geochronological record reported in the literature (Alvarado & Gans, 2012; Gazel et al., 2011; MacMillan et al., 2004). $^{40}Ar/^{39}Ar$ data were collected at the New Mexico Geochronology Research Laboratory (details in supporting information Table S1).

Samples with no visible weathering, as verified by petrographic studies, were crushed in an alumina jaw crusher and washed with deionized water in an ultrasonic bath. Alteration-free rock chips (e.g., those free of oxides, veins, and zeolites) were selected under stereoscopic microscope and powdered in an alumina mill. Homogenous glass disks were produced at Michigan State University by fusing each powdered sample with lithium tetraborate ($Li_2B_4O_7$). Glass disks were then analyzed for major elements and selected trace elements (e.g., Cr, Cu, Ni, Sr, Rb, Zr, and Zn) by X-ray fluorescence in a Bruker S4 Pioneer. Trace elements were obtained in the same glass disks by laser ablation inductively coupled plasma mass spectrometry in a Micromass Platform inductively coupled plasma mass spectrometry with a Cetac LSX 200+ Nd:YAG. Analytical methods, precision, and accuracy are as reported in Hannah et al. (2002).

Radiogenic isotope analyses were conducted in the Isotope Geochemistry Laboratory at the University of North Carolina-Chapel Hill (Table S2 in the supporting information). Select powdered samples (500 mg) were digested with a mixture of $HF+HNO_3$ in Teflon beakers.

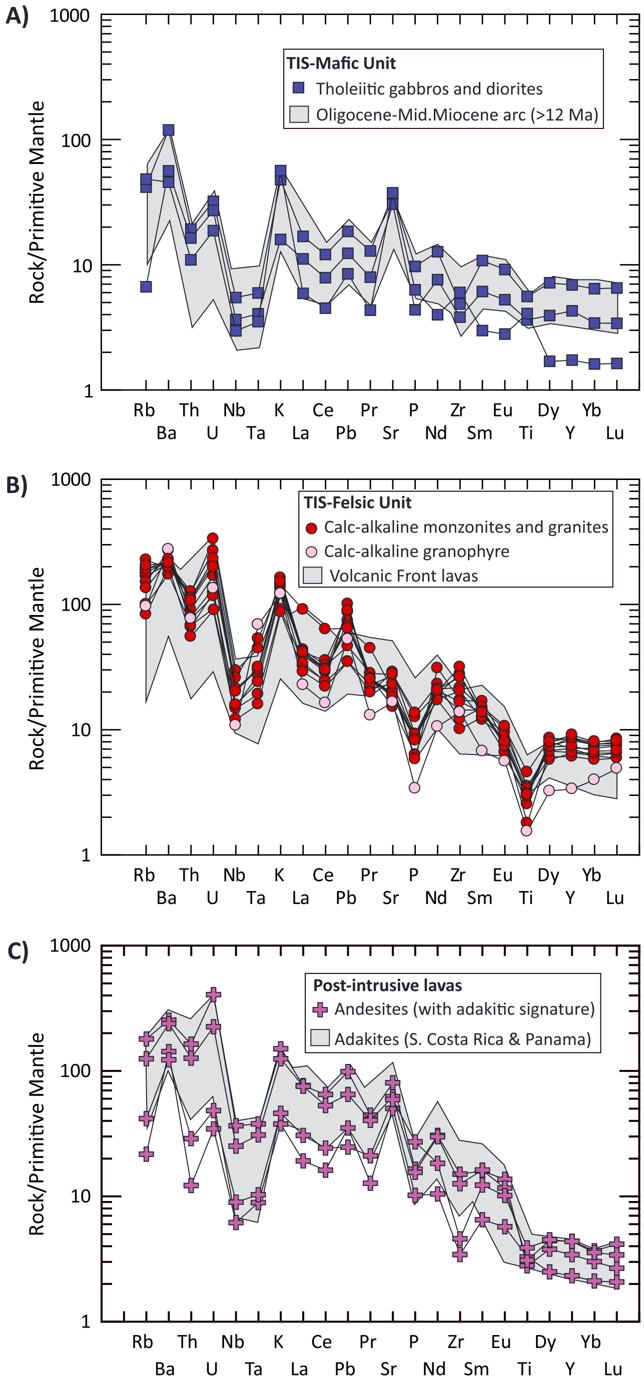

Figure 3. Multielement diagrams normalized to Primitive Mantle (McDonough & Sun, 1995) for the samples collected in this study in the Talamanca Cordillera. (a) Mafic suite, (b) felsic suite, and (c) postintrusive lavas. Literature data (gray fields) for comparison are from Gazel et al. (2009), Gazel et al. (2011), and Carr et al. (2014). TIS = Talamanca Intrusive Suite.

These solutions were placed on a hotplate for three days at a temperature of 165 °C. Each sample was dried and redissolved in HCl. After their dissolution, three aliquots were separated for Sr, Nd, and Pb, each one containing 5 mg of sample; these aliquots were dried and redissolved in the appropriate acid solution to undergo ion exchange chromatography columns (Gray et al., 2008). Elemental separates were analyzed using a Micromass VG Sector 54 thermal ionization mass spectrometer. Strontium measurements were normalized to $^{86}Sr/^{88}Sr$ = 0.1194, and Nd isotopes to $^{146}Nd/^{144}Nd$ = 0.7219. Standard replicate measurements yielded a mean $^{87}Sr/^{86}Sr$ = 0.710257 ± 0.000022 (2σ) for NBS 987, a mean $^{143}Nd/^{144}Nd$ = 0.512112 ± 0.000011 (2σ) for JNdi-1, and a mean $^{206}Pb/^{207}Pb$ = 1.0940 ± 0.0003 (2σ; Coleman et al., 2004; Gray et al., 2008). The laboratory long-term average measured $^{206}Pb/^{207}Pb$ = 1.0940 ± 0.0003 (2σ) for NBS-981 with a mean fractionation correction of 0.098 ± 0.008% per amu (Coleman et al., 2004; Gray et al., 2008). For $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$, these yields fractionation corrections of −0.20 ± 0.016%, −0.30 ± 0.024% and −0.40 ± 0.032%, respectively.

To determine the volume of the exposed areas in the different arc segments we produced a regional digital elevation model based on Becker et al. (2009). We interpolated elevation points each 30-arc sec resolution using a Kriging method and cell size of 1,109 m by 1,109 m. For area and volumetric calculations, the digital elevation model was projected to planar local Costa Rica Coordinates (CRTM05 projection). Exposed ranges and volcanic arc were delimited based on their geomorphological expression and surface area were calculated. For volume calculations we used the base of the exposed range or arc as reference. Interpolations, delimitations, area, and volumetric calculations were performed using algorithms of the ArcMap software, version 10.3.

4. Results

4.1. Age Data

We produced five new $^{40}Ar/^{39}Ar$ step heating ages of biotite separates in three intrusive rocks and matrix in two postintrusive lavas, but only four yielded plateau ages (supporting information Table S1 and $^{40}Ar/^{39}Ar$ results). Analytical results, age spectra, and inverse isochron diagrams are also provided in the supporting information. The new ages for intrusive suites (biotite separates from samples 19F-1, 28-5, and 29-3) range from 10.02 ± 0.02 to 9.96 ± 0.01M in agreement with the ages reported previously for felsic intrusive rocks in other locations of the Talamanca Cordillera (Alvarado et al., 1992; Alvarado & Gans, 2012; De Boer et al., 1995; Drummond et al., 1995; MacMillan et al., 2004). We also report a new age of 1.72 ± 0.05 Ma (groundmass from sample 03-3), for postintrusive volcanic rocks with adakitic affinity. This age is in agreement with the previously published ages by Abratis and Wörner (2001), MacMillan et al. (2004), and Gazel et al. (2011), for adakitic-like lavas in southern Costa Rica.

4.2. Petrology and Geochemistry

We collected major and trace element data for 20 new samples reported in the supporting information (Table S2, Geochemistry Results). The new analytical data include samples from the following stratigraphic sequence: preintrusive volcanic rocks (1), intrusive rocks (15), and postintrusive volcanic rocks (4).

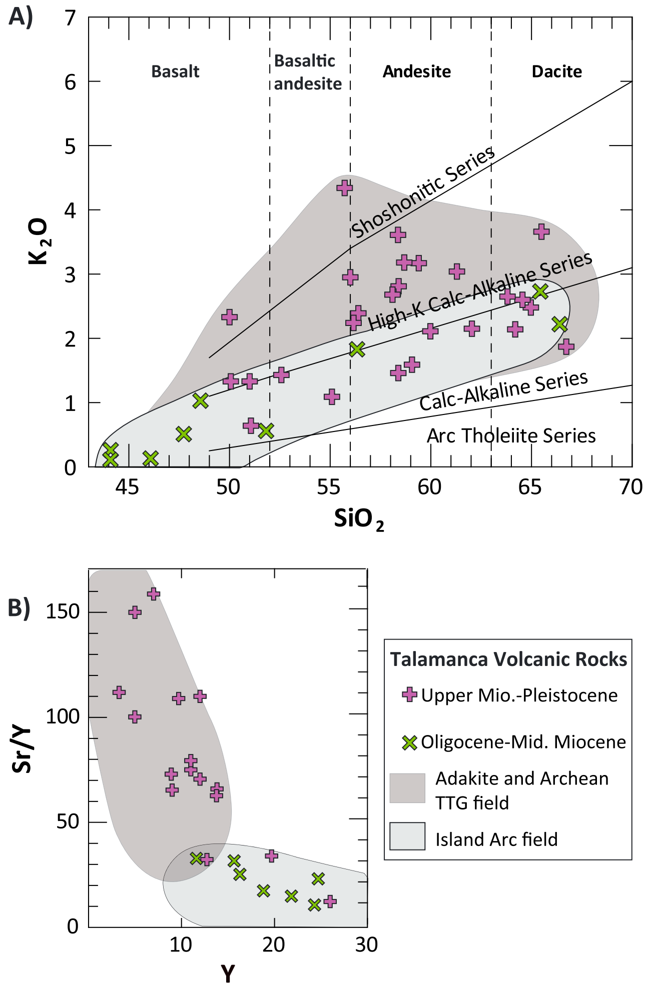

Figure 4. Geochemical characteristics of Talamanca volcanic rocks collected in this study. (a) Diagram from Peccerillo and Taylor (1976) displaying the calc-alkaline series for Early-Middle Miocene and calc-alkaline to shoshonitic series for Upper Miocene-Pleistocene samples. (b) Sr/Y versus Y plot, areas that define Archean tonalite, trondhjemite, and granodiorite (TTG) suites/adakites and island arc field according to Defant et al. (1991). Additional data compiled from Drummond et al. (1995), Abratis (1998), and Gazel et al. (2009, 2011).

4.2.1. Preintrusive Volcanic Rocks

Preintrusive basaltic rocks from the Talamanca Cordillera have a similar mineral paragenesis (olivine, ±cpx and lack of opx) as reported by Gazel et al. (2009) for Oligocene to mid-Miocene volcanic rocks found elsewhere in southern Central America. These lavas are mafic and typically include phenocrysts of plagioclase, clinopyroxene, and minor olivine. Sample from this unit are tholeiitic basalts depleted in incompatible trace elements relative to the rest of units analyzed for this project (Table S2, Geochemical Results).

4.2.2. Talamanca Intrusive Suite

According to the normative compositions (Ab-An-Or; Figure 2a), our samples can be separated into a felsic unit (granodiorites to granites) and a mafic unit (mostly tonalites). Field evidence (crosscutting relations and xenoliths in the felsic unit) suggests that the mafic unit represents earlier magmas within the intrusive suite. These rocks contain megacrysts of plagioclase, clinopyroxene, and amphibole (*magnesio hornblende*) and biotite as common accessory phase. The felsic unit includes mostly monzonites and granites. The rocks are composed of plagioclase, K-feldspar, quartz, clinopyroxene and orthopyroxene, amphibole and biotite, with magnetite, zircon, apatite, and tourmaline as accessory phases. This unit also includes granophyres, aplites, and pegmatite dikes. Field evidence (lack of chilled margins and plastic deformation) suggests that these small dikes are synintrusive and may represent residual liquids at the end of crystallization. These rocks are characterized by a micrographic intergrowth of quartz and feldspar. The mineral paragenesis includes plagioclase, K-feldspar, quartz (with inclusions of apatite and zircon), and biotite with tourmaline (schorl) as a common accessory phase.

The felsic unit mostly belongs to the calc-alkalic series and the mafic unit is predominantly calcic (Figure 2b). Rocks from the Talamanca Intrusive Suite are principally metaluminous intrusions (Figure 2c, after Maniar & Piccoli, 1989). Minor peraluminous facies (granophyre 24-3 and other alkali granites) are restricted to small, vein-like intrusions that possibly represent residual liquids from the principal intrusive bodies. Primitive mantle normalizations of all instrusive samples (Figure 3) show clear enrichments in large-ion lithophile elements (e.g., Rb, Ba, K, and Pb) and depletions in high-field strengh elements (e.g., Nb, Ta, and Ti) typical of subduction-related magmas (e.g., Pearce & Peate, 1995). The mafic unit is depleted in light rare earth element (LREE; La_N/Yb_N = 2.61–3.65) relative to the felsic unit that records higher LREE concentrations (La_N/Yb_N = 4.37–12.76). The felsic unit (except for one granophyre, 24-3) also shows negative europium anomalies (Eu/Eu* = 0.58–0.91).

4.2.3. Postintrusive Volcanic Rocks

The postintrusive rocks include lavas and pyroclastic flows, occasionally separated by clear paleosols. These lavas are porphyritic with phenocrysts of plagioclase and clinopyroxene. Olivine is restricted to the basalts and orthopyroxene (hypersthene) to the andesites. Hornblende and biotite are common accessory phases. Geochemically, the postintrusive rocks are classified as basalts, basaltic andesites, and trachy-andesites, ranging from the calc-alkaline to the shoshonitic series (Figure 4a). Most of the postintrusive samples collected in this study have geochemical signatures similar to adakites (as defined by Defant et al., 1991; Defant et al., 1992) with Sr = 1,000–1,602 ppm, Sr/Y = 62–109, La/Yb = 13–37, and Nb, Ti, and Zr negative anomalies (Figure 4b) and depleted heavy rare earth element compositions. Adakites were previously reported in western Panama (Defant et al., 1991; Defant et al., 1992) and the Talamanca Cordillera (Abratis & Wörner, 2001; Gazel et al., 2011). This study shows that this type of magmatism was probably more extensive than previously reported. Hereafter, we use the term "adakite" to refer to primitive or magnesian andesitic

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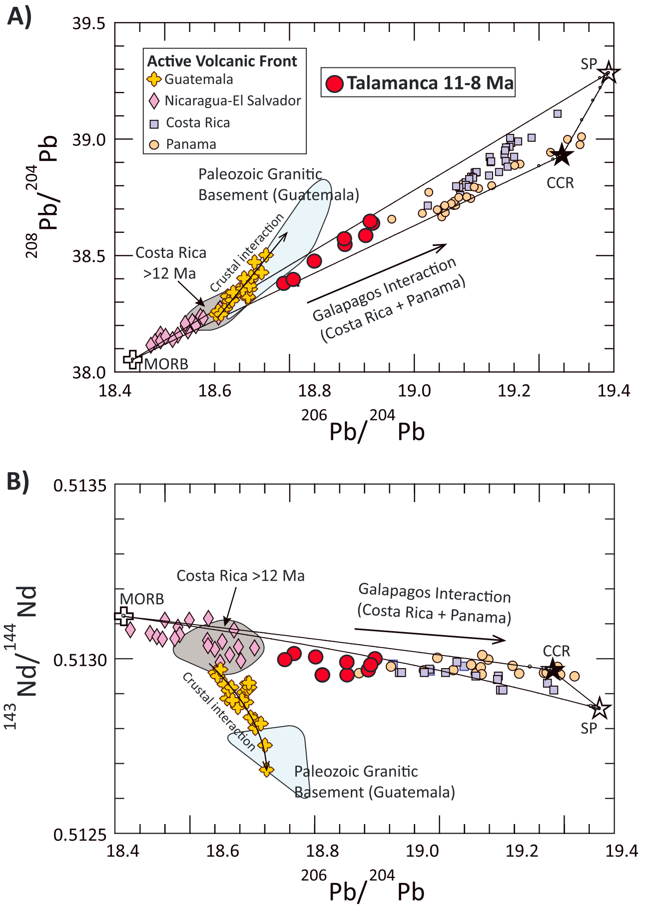

Figure 5. Pb-Nd isotopes systematics for magmas of the Central America Volcanic Arc. The mixing lines connect the required end-members, local depleted mantle (mid-ocean ridge basalt, MORB), the subducting Seamount Province (SP), and the Cocos/Coiba Ridge (CCR) offshore of Costa Rica (Gazel et al., 2009). The Galapagos signature systematically decreases north along the volcanic front from central Costa Rica/Panama toward Nicaragua. Note that only some samples from Guatemala are affected by preexisting continental crust. The shaded area includes samples from the Costa Rican arc that are 12–25 Ma; notice how they overlap with the modern Nicaraguan volcanic front and the new Talamanca Suite rocks represent a transition between those samples and the modern volcanic front (<1 Ma) of Costa Rica and Panama. Additional data from Feigenson et al. (2004), Gazel et al. (2009), and Heydolph et al. (2012).

magmas interpreted to be derived from the melting of mafic protolith (subducting oceanic crust and lower crust) within the garnet stability field (Martin et al., 2005; Moyen, 2009) and the subsequent reaction of these melts with the mantle wedge (Defant & Drummond, 1990; Kay, 1978).

4.3. Radiogenic Isotopes

We collected Sr-Nd-Pb isotopes for five key samples (three intrusive rocks and two volcanic rocks) reported in Table S2 (Geochemical Results, supporting information). Age-corrected ratios are plotted in Figure 5. These new data help fill the gap in the evolution of the arc, plotting between the Oligocene-Miocene Arc >12 Ma, and the modern lavas from the active volcanic front <5 Ma, trending along the correlation controlled by interaction with Galapagos tracks (Gazel et al., 2009; Hoernle et al., 2008) rather than crustal contamination from pre-arc continental crustal as shown by samples from the Guatemala Volcanic Front (Feigenson et al., 2004; Heydolph et al., 2012).

5. Discussion

5.1. Geochemical Evolution From an Intraoceanic Arc to a Young Continent

Continental crust is andesitic in composition and enriched in elements incompatible in the mantle (e.g., K_2O and LREE; e.g., Taylor & McLennan, 1995; Rudnick & Gao, 2003). These incompatible elements are fractionated by melting and crystallization processes, possibly at different stages (e.g., Rudnick & Gao, 2003). Although silicic magmas ($SiO_2 > 60$ wt%) are common in arc systems, most arcs produce magmas with bimodal distributions dominated by basaltic compositions with a minor population of silicic melts within continental crust values, and very low K_2O < 1 wt% (Gazel et al., 2015). In contrast, samples from the Talamanca Cordillera are within the SiO_2, K_2O, and Mg# (molar MgO/MgO + FeO) range of average continental crust (Rudnick & Gao, 2003), reaching even upper crust values and Archean TTG compositions (Figure 6).

Together with the production of magmas with major element compositions within the range of continental crust compositions in the Talamanca Cordillera, there was also a shift in trace element signatures (Figure 7). Before the Middle Miocene (>12 Ma) the trace element signatures were depleted in incompatible elements and overall compositions common to most intraoceanic arcs (Gazel et al., 2015). In contrast, Late Miocene igneous rocks (11–6 Ma) have incompatible element compositions very similar to average upper continental crust and Archean TTG, with a few differences in some incompatible elements like Ba and U. Those differences can be explained by the presence of a thick carbonate package in the subducting sediments in the Cocos Plate with particular elevated concentrations of those elements (Patino et al., 2000). Samples with ages <6 Ma, including the active volcanic front lavas, also show very similar incompatible elements patterns in comparison to upper continental crust and TTG estimates, with the exception of Ba, as explained above and of Pb, which shows depletions that can be explained by the interaction of subducting Galapagos seamounts that are depleted in Pb relative to other incompatible elements as observed in many intraplate settings.

5.2. The Role of Melting of Enriched Oceanic Crust in the Generation of Juvenile Continental Crust Material

It has been known for nearly a century that fractional crystallization can result in silicic melts (Bowen, 1928), but unless primary magmas start with enriched compositions, fractional crystallization itself will not produce the incompatible element composition of continental crust (Kelemen, Hanghøj, et al., 2003;

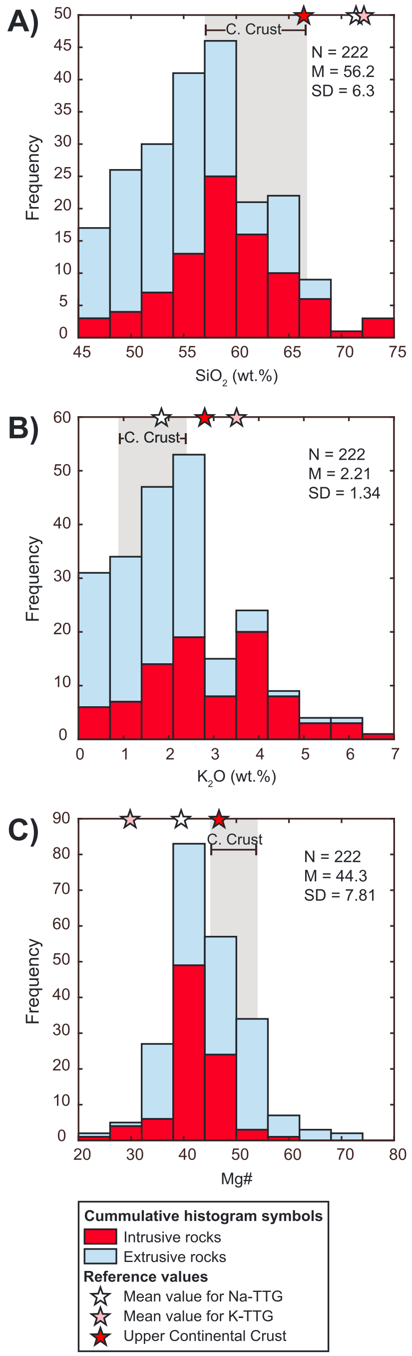

Figure 6. Histograms showing the distribution of SiO_2, K_2O, and Mg# compositions for igneous rock samples (n = 78) of Talamanca Cordillera. Most of the samples range between compositions that correspond to average continental crust to upper continental crust and Archean TTGs. (a) Frequency histogram of SiO_2, (b) frequency histogram of K_2O, and (c) frequency histogram of Mg#. Gray area represents the range of continental crust estimates according to Kelemen, Yogodzinski, et al. (2003) and Gazel et al. (2015). Average upper continental crust from Rudnick and Gao (2003) and average sodic (Na) and potassic (K) TTG from Moyen (2011). Samples from this study and additional data compiled from literature (Abratis, 1998; Ballmann, 1976; Bolge et al., 2009; Carr et al., 2014; Drummond et al., 1995; Gräfe, 1998; Gazel et al., 2009; Jackson, 1991; Tournon, 1984). TTG = tonalite, trondhjemite, and granodiorite.

Vogel et al., 2006). Although subduction-related fluids enrich the incompatible elements composition in arc settings relative to mid-ocean ridge basalt (MORB) mantle, this process itself is also not sufficient to produce magmas that resemble early continental crust, and therefore, other processes must be explored (Class et al., 2000; Elliott et al., 1997; Plank & Langmuir, 1993).

The edges of oceanic plateaus have been proposed as the places for the onset of subduction and gradual production of juvenile continental material (Gerya et al., 2015; Stein & Goldstein, 1996; Whattam, 2018). This is an important model to consider because the arc in southern Central America developed in the westernmost edge of the Caribbean Plateau (e.g., Denyer & Gazel, 2009; Hauff et al., 2000). Nevertheless, as shown in Gazel et al. (2015) the continental crust signature appeared in pulses in the record of the Central American land-bridge, tracing the interaction with Galapagos tracks, rather than steady state evolution. Additionally, Hoernle et al. (2008) showed that the isotopic signature of the subducting Galapagos tracks are zoned and that zonation is followed by output in the active volcanoes, of particular interest is the “seamount province signature” that is not found in older Galapagos terranes (Gazel et al., 2018) confirming that there is a need of a “recent” Galapagos input represented by these subducting seamounts. Finally, the Miocene Arc (samples >12 Ma) also developed in the same plateau basement and not only lacks the Galapagos signature but is also depleted in trace elements. Thus, the Miocene Arc lacks the continental characteristics of modern volcanic rocks <12 Ma.

Lower crustal fractionation of water-saturated magmas in the garnet + amphibole stability field beneath the Central America Arc has been proposed as the mechanism for formation of large volumes (~10^2 km^3) of adakite magmas (Hidalgo & Rooney, 2010, 2014). Also, anatexis of lower crustal plutons (Vogel et al., 2004) can explain the presence of voluminous silicic explosive volcanism. Although these processes can reliably explain the evolution of felsic melts, these mechanisms do not explain the generation of contemporaneous primitive basalts and primitive andesites with a clear isotopic and trace element Galapagos signature after 12 Ma found in Costa Rica and Panama (Gazel et al., 2009, 2015).

It is thus necessary to evoke a process that will result in the production of primitive melts with both a Galapagos isotopic signature and major and trace element systematics that resemble juvenile continental crust. We propose that hydrous partial melting of the subducting slab and the reaction of those melts with the mantle wedge (Defant & Drummond, 1990; Defant et al., 1992; Kay, 1978; Kelemen, Hanghøj, et al., 2003; Kelemen, Yogodzinski, et al., 2003; Yogodzinski et al., 1995, 2015) can effectively explain this evolution. In the particular case of Central America, the slab component is already enriched in incompatible elements by intraplate processes (Gazel et al., 2009; Hoernle et al., 2008). This enriched subducting component can provide the missing incompatible element budget necessary for arc to reach early continental crust values as reported in the literature (e.g., Rudnick & Gao, 2003). An intraplate input can occur when the eruptive products of a mantle plume (e.g., ridges and seamount tracks) get recycled in a subduction system (Gazel et al., 2009). The partial melting of subducting, plume-derived material carried by the slab can “refertilize” the arc mantle wedge; the subsequent melting of this

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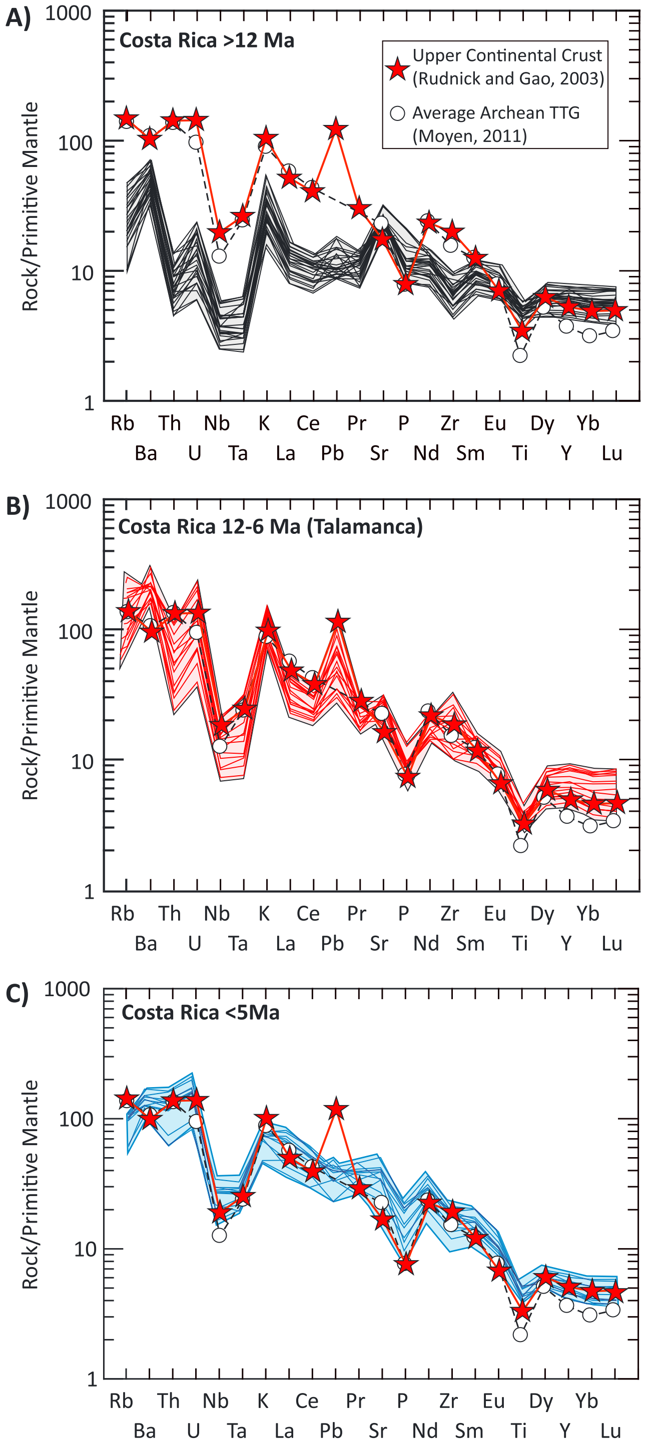

Figure 7. Primitive-mantle normalized (McDonough & Sun, 1995) multielement diagram for Costa Rica arc samples with Mg# > 45 and SiO_2 > 55 wt%. (a) Oligocene to Middle-Miocene >12 Ma, (b) Late Miocene (12–6 Ma), and (c) Recent (<5 Ma) samples, compared with average upper continental crust values from Rudnick and Gao (2003) and Archean TGG (Moyen, 2011). Additional data compiled from Drummond et al. (1995), Gräfe (1998), Abratis (1998), Gazel et al. (2009), Bolge et al. (2009), and Carr et al. (2014). TTG = tonalite, trondhjemite, and granodiorite.

metasomatized mantle can produce the geochemically enriched lavas in an arc setting, much like the observed enriched suites in the Talamanca Cordillera. This process is possible as thermal models indicate that temperatures above the aqueous fluid saturated solidus are common along the top of most subducting plates worldwide (Conder, 2005; Kelemen et al., 1990; van Keken, Kiefer, et al., 2002; Peacock et al., 2005). Also, even if the slab P-T path is not hot enough to cross the wet solidus of eclogite, buoyant diapirs of slab material can potentially detach from the subducting slab and enter a regime of elevated temperatures in the mantle wedge that can cause devolatilization and melting of those materials (Behn et al., 2011; Gerya & Yuen, 2003; Hacker et al., 2011; Marschall & Schumacher, 2012). Lower crustal fractionation (Hidalgo & Rooney, 2010; Hidalgo & Rooney, 2014) and/or anatexis of lower crust materials (Vogel et al., 2004) will later add to the evolution of primary magmas into even more felsic compositions.

To quantitatively test the effect of the interaction of enriched Galapagos tracks in the geochemical evolution of the arc in Costa Rica, we modeled our data using Arc Basalt Simulator (ABS) Models (Kimura et al., 2009). To evaluate the data, we first produced as mean "target" composition of samples with SiO_2 > 55 wt%, for the Oligocene-Miocene (>12 Ma), Upper Miocene (12–8 Ma) and samples >5 Ma (including the active volcanic front). We used the partial melting and metasomatism models in ABS with the sources and parameters described in Gazel et al. (2009), slab P-T paths from van Keken, Hauri, et al. (2002) calibrated to mantle wedge conditions from Gazel et al. (2011; temperatures 1350 °C, for samples >6 Ma, and 1450 °C for samples <6 Ma). We allowed variations within 20–30% for most elements for the accepted successful results to reproduce the natural variation with the samples with the exception of Ba, K, and sometimes Sr that required more flexibility due to the tendency of ABS to overestimate these elements. We later optimized these "fluid-mobile" element results by multiplying the ABS result by a factor that will reach the target value (all model results are in Table S3, supporting information). Future work using this empirical approach can help improve the partition coefficients used for modeling of fluid-mobile elements.

Model results from 100,000 Monte Carlo simulations using ABS are plotted in Figure 8. We first modeled the >12-Ma samples with sediment and altered MORB slab, and after 100,000 simulations we did not obtain a single successful result. After replacing the composition from altered MORB slab to the average subducting Cocos Ridge for samples 11–5 Ma and the average Seamount Province for samples <5 Ma, successful results were reached in the first tens of simulations. These results suggest that the samples <12 Ma (the ones close to upper continental crust values) indeed require an enriched subducted component from the subducting Galapagos tracks. While the samples >12 Ma can be reproduced with a subduction component composed of an altered MORB slab and sediments and do not require a Galapagos track component. The >12-Ma magmas are very similar in composition to magmas from the Nicaraguan Volcanic Front that were also successfully modeled by melting a depleted mantle that was metasomatized by components from subducting MORB slab and sediments (Saginor et al., 2013).

In a regional context, from Nicaragua to Costa Rica, the size and volume of active volcanoes increase toward the southeast, indicating an increase

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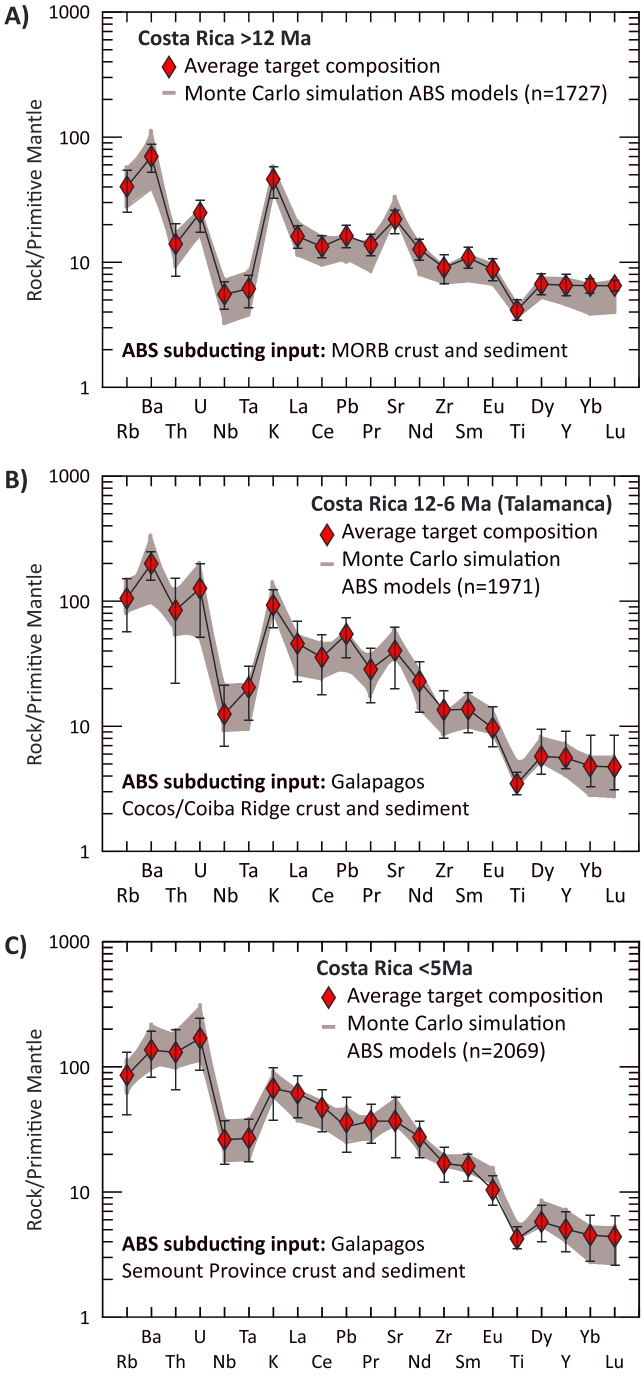

Figure 8. Results of multielement modeling using Monte Carlo simulations with Arc Basalt Simulator (ABS, Kimura et al., 2009). (a) Oligocene to Middle-Miocene >12 Ma, (b) Late Miocene (12–6 Ma), and (c) Recent (<5 Ma). A Galapagos subduction input is necessary to reproduce samples <12 Ma, while samples >12 Ma from the Miocene Arc were reproduced by an altered mid-ocean ridge basalt subducting slab. Fluid mobile elements, Ba and Rb, were optimized by multiplying ABS result by a factor that will reach the target value, as ABS results overestimated these elements by more than 100% of the target concentrations.

in melt productivity (Carr et al., 2007). We expanded these calculations to the area and volume of exposed volcanic front rocks from Nicaragua, Northern Costa Rica, Central Costa Rica and the Talamanca Cordillera. To make this assessment, we first delimited those arc segments based on the work of Carr et al. (2007), Denyer and Alvarado (2007), and Saginor et al. (2011). The rock volumes were calculated from the base level (Nicaragua: 0 m/sea level, North Costa Rica: 200 m, Central Costa Rica: 200 m and Talamanca: 520 m) in order to avoid including recent sedimentary material (Table S3). Overall, there is an increase in the mean height, area, and exposed volume from Nicaragua to Costa Rica, with the highest area and volume exposed in the segment delimited for the Talamanca Cordillera (Figure 9). Because we can only calculate these parameters taking into consideration the exposed material, we decided to plot the ratio of volume/exposed area of the arc segment to examine if the productivity of the magmatic output increases along strike (Figure 9). The increasing ratio along the volcanic front suggests that the magmatic productivity does increase toward the area where the Galapagos tracks are subducted. We suggest that this may be controlled by a more fertile source beneath Costa Rica that resulted from the mestasomatism of the mantle wedge with melts from the subducting Galapagos tracks. This is a similar geodynamic context as Ecuador, where the melt productivity increases in the region where the Carnegie Ridge subducts, generating high volumes of magma with continental crust signatures (Martin et al., 2014). Nevertheless, it is also important to consider that these calculations, especially for Talamanca, represent a general idea of productivity limited to 8–12 Ma as much has been lost to erosion, and uplift is not clearly known. The rest of the segments represent a time window in the last 5 Ma.

5.3. Seismic Evidence of a Transition From an Arc to a Young Continent

Two wide-angle seismic refraction experiments were conducted in 2005 and 2008 to elucidate the subsurface structure of the Costa Rican volcanic arc (Gazel et al., 2015; Hayes et al., 2013). The onshore portion of these profiles transects a total of 152 km from the Pacific forearc across the extinct Miocene Arc and the present-day active arc (Figure 10). The 2008 onshore-offshore survey extends ~500 km and provides additional constraints on the seismic structure of the Caribbean Plate and arc's lower crust (Gazel et al., 2015). Wide-angle refractions and reflections from these experiments were processed using raytracing inverse methods yielding a cross-sectional profile of seismic *P* wave velocities (survey details, methods, and models available in Gazel et al., 2015). Here we use 1-D velocity-depth profiles from these previously published inversions to compare the seismic velocity signatures of the active arc, the Miocene Arc, and the Caribbean oceanic crust with velocities of continental crust and other modern arcs (Figure 10).

Seismic velocities within the Caribbean Plate are well constrained by dense raypath coverage and show a relatively uniform lateral structure offshore Costa Rica (Gazel et al., 2015). The offshore 1-D profile shows velocities consistent with a thick mafic large igneous province where velocities rapidly approach >7 km/s between 7- and 20-km depths [Figure 10]. Furthermore, gravity models of this section of Caribbean crust reveal densities consistent with mafic compositions (i.e., >3 g/cm^3). Additionally, the section of the arc that comprises the

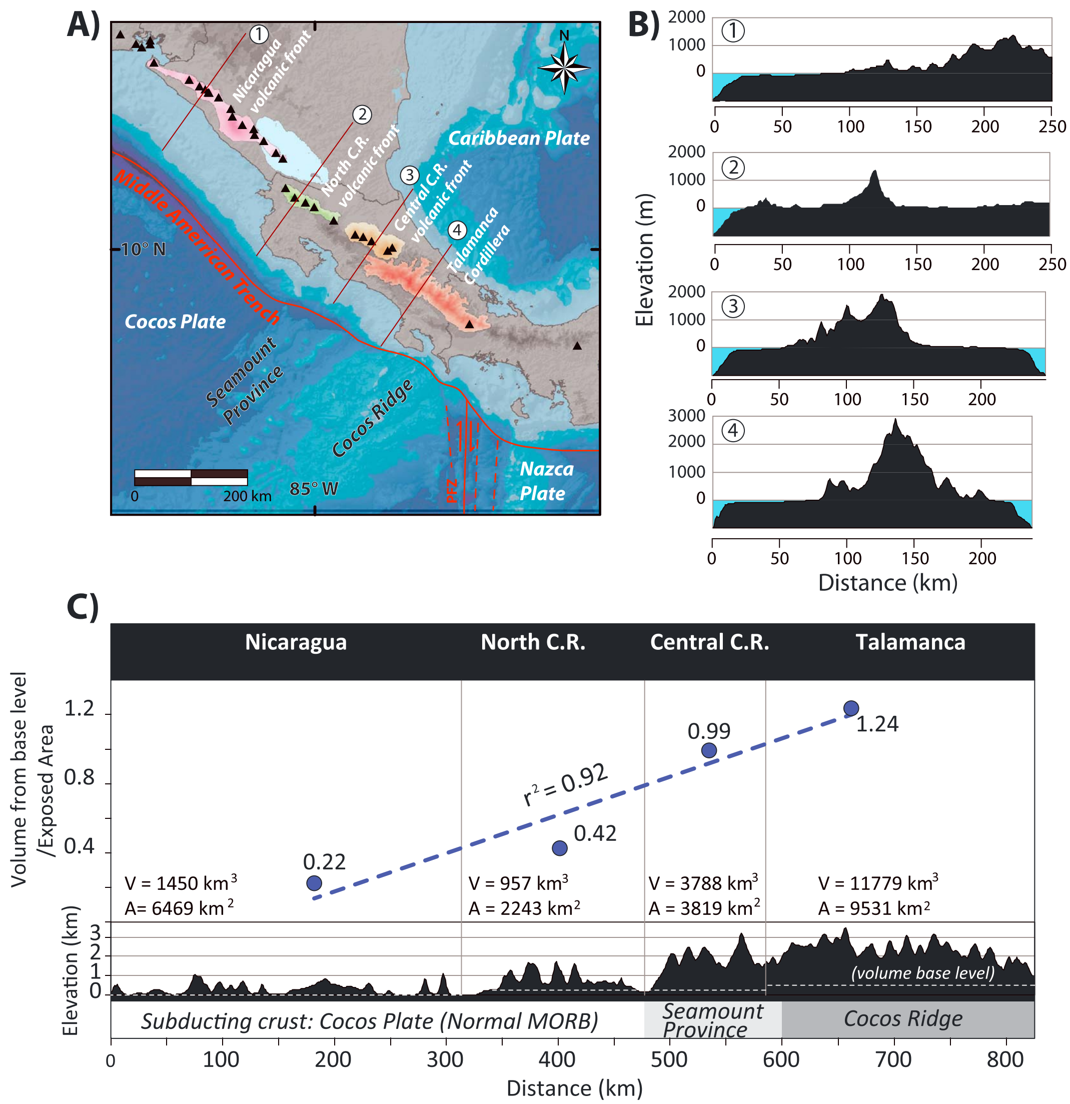

Figure 9. Magmatic volumes as a proxy for productivity along the volcanic front and its relation to the segmentation of subducting input. (a) Segments from Nicaragua to southern Costa Rica selected for calculations together with the tectonic setting of the volcanic front. (b) Topographic profiles of 1. NW Nicaragua volcanic front, 2. North Costa Rica, 3. Central Costa Rica, and 4. Talamanca Cordillera. (c) Volume and area estimates for the different segments and correlation of average height with the subduction of Galapagos tracks in Costa Rica. MORB = mid-ocean ridge basalt.

Talamanca Cordillera stand in a continental-like crust thickness, >40 km according to Airy-type isostasy modeling of the Moho depth (Dzierma et al., 2010) or 32–36 km, according to regional 3-D density modeling by Lücke (2014).

Seismic velocities along the modern arc in Costa Rica compared with other active arcs and average continental crust suggest a transitional composition beneath the active arc in Costa Rica (Gazel et al., 2015; Hayes et al., 2013). Although inferring SiO_2 content from seismic velocity is challenging, Hacker et al. (2015) show that lower crust with *P* wave velocities >7.0–7.2 km/s must be mafic. The 1-D velocity-depth profile beneath the Miocene Arc shows velocities >7.0–7.2 km/s between 15- and 22-km depths. Comparisons between the 1-D seismic velocity profiles in the middle and lower crust beneath the active arc and remnant Miocene Arc (i.e., higher velocities in the Miocene Arc) suggest a transition toward more felsic compositions as the volcanic center migrated toward the location of the modern arc (Figure 10). These observed variations in seismic velocities between the Miocene Arc and the modern arc are consistent with earlier seismic velocity models from earthquake tomography (Husen et al., 2003). Furthermore, compilations of seismic velocities in

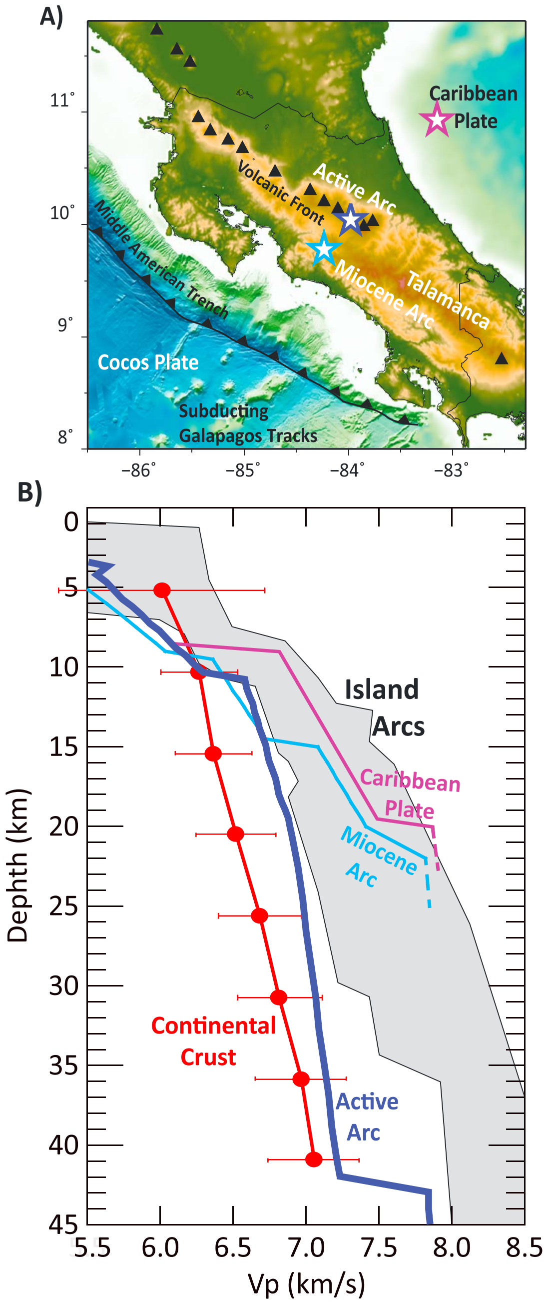

Figure 10. One-dimensional velocity-depth profiles results. (a) Locations of the 1-D velocity-depth profiles. (b) Results of the different tomographic inversions to compare the seismic velocity signatures of the active arc (dark blue), the Miocene Arc (light blue), and the Caribbean oceanic crust (purple) with velocities of continental crust (red; Christensen & Mooney, 1995) and other modern arcs (Calvert, 2011). Note that in the lower crust the Miocene Arc is more similar to other modern oceanic arcs and Caribbean oceanic crust compared to the modern arc. The modern arc is a low velocity extreme compared to other active arcs and more similar to continental crust at depth.

modern intraoceanic arcs (Calvert, 2011), which range in bulk composition from intermediate to mafic, show that the Miocene Arc is similar to other modern volcanic arcs, whereas the active arc is closer to continental crust estimates.

While these seismic velocity profiles are consistent with observed geochemical observations at the surface and are thus potentially related to compositional differences at depth, seismic velocities may also be influenced by variations in temperature, pressure, hydrothermal fluid content and the presence of partial melts (Hacker & Abers, 2004, and references therein). Seismic velocity decreases as temperatures increase with typical coefficients of about 2–6 × 10^{-4} km/s/°C (Christensen, 1979; Holbrook et al., 1992; Kern, 1978). Using these coefficients, observed differences between seismic velocities in the lower crust beneath the modern arc and the Miocene Arc of ~0.6 km/s would yield temperature differences in these two profiles between ~300 and 1000 °C. The production and transport of melt beneath the modern arc would likely produce such temperature differences, though it is difficult to assess scales of thermal heterogeneity relative to the resolution of these seismic studies. Further work to assess the *P* wave to *S* wave velocity ratios are needed to further constrain temperature, melt, and fluid contents beneath the modern arc.

The geophysical evidence from both gravity (Lücke & Arroyo, 2015) and seismic studies (Husen et al., 2003) is consistent with the geochemical evolution of the arc (Gazel et al., 2015), and though results presented here may favor the subduction model. In summary, the Miocene arc depleted in incompatible elements is characterized by normal arc velocities while the modern arc that resulted from the subduction system interaction with Galapagos tracks record seismic velocities and structure similar to continental crust. Future geophysical and geochemical studies in the Talamanca Cordillera are needed to help resolve the many processes involved in this transition. Understanding the processes in the natural laboratory of the Talamanca Cordillera may be key to elucidating the conditions and processes that produced Earth's early continental crust.

6. Global Comparison of the Talamanca Intrusive Suites With Other Arc-Related Plutonic Examples

As discussed in previous sections, the Talamanca Cordillera intrusive rocks record the transition from an oceanic to a continental arc. In this section, we compare this intrusive suite with other examples of arc-related plutonic rocks from the Marianas, Aleutians, Virgin Islands, and the Sierra Nevada Batholith. All of these suites share similarity with Talamanca that did not develop into preexisting cratonic continental material, and therefore can be used to investigate the processes involved in the generation of juvenile continental crust globally.

The Mariana islands forearc plutonic rocks (48–43 Ma) compared with the Talamanca suite are characterized by overall depletions in incompatible elements (Figures 11 and 12). These rocks are thought to belong to the initiation of subduction in the Western Pacific, possibly representing derivative magmas that fractionated from contemporaneous boninitic parental magmas (Johnson et al., 2014). Below the Mariana frontal arc seismic velocities range from 5.0 to 6.5 km/s above 12-km depth and increase to 6.6–7.4 km/s between 12 and 20 km and are >7.6 km/s between 20 and 30 km (Calvert et al., 2008). These velocities suggest a more mafic composition for the deep sections of the

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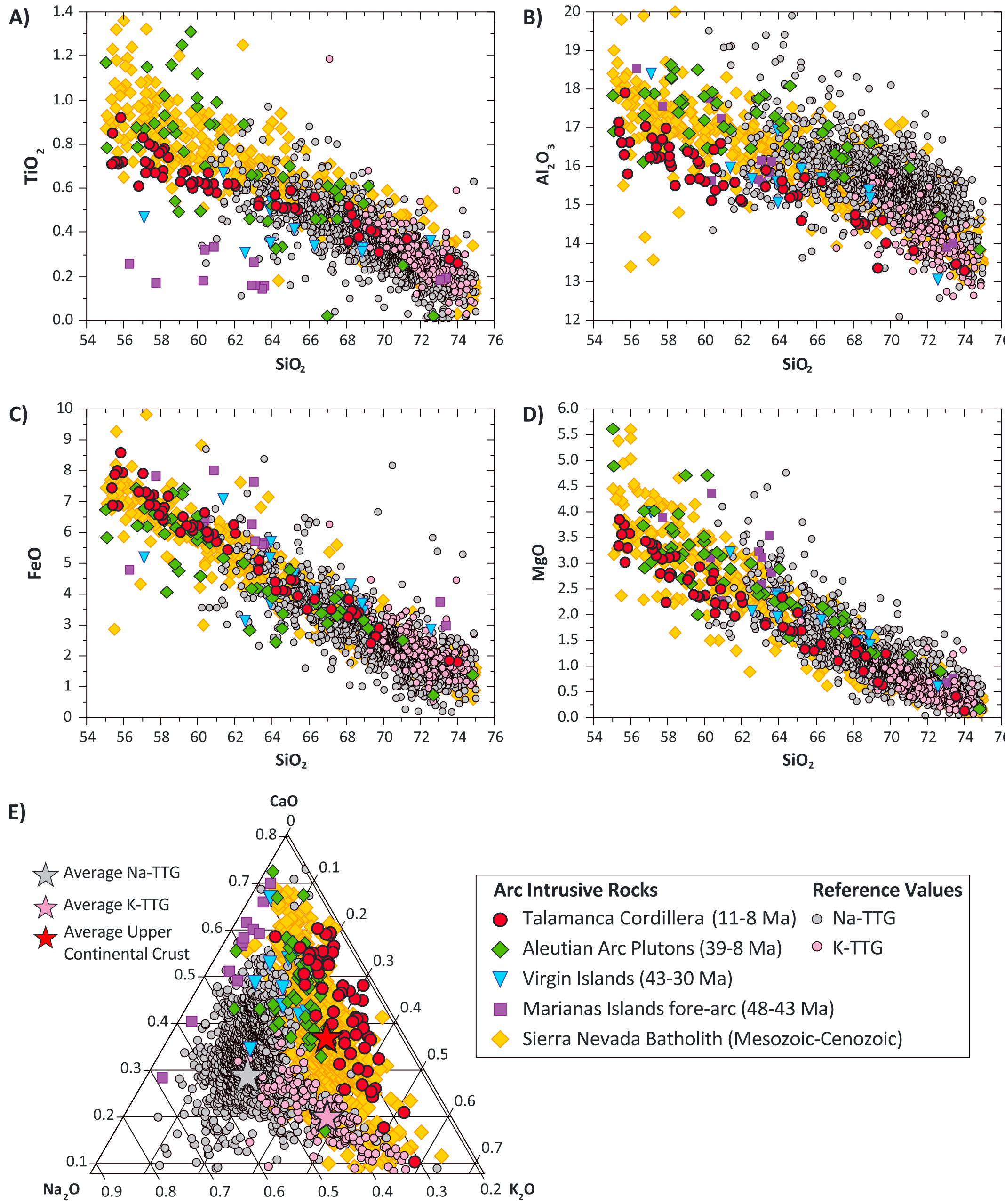

Figure 11. Global comparison of Talamanca intrusive rocks, other arc plutonic rocks, and reference compositions of sodic (Na) and potassic (K) TTGs (Moyen, 2011) and Upper Continental Crust (Rudnick & Gao, 2003). Talamanca data from Ballmann (1976), Gräfe (1998), Abratis (1998), Drummond et al. (1995), Wegner et al. (2011), and this study. Kagalaska pluton from Fraser and Barrett (1959), Citron (1980), Kay et al. (1983), Kay et al. (1986, 1990), Romick et al. (1990), Tsvetkov (1991), Yogodzinski et al. (1995), and Cai et al. (2015). Virgin Islands data from Schrecengost (2010), Georoc database (consulted 01-11-2018). Mariana forearc data from Johnson et al. (2014). Sierra Nevada Batholith data from NAVDAT (consulted 11-04-2017). All samples within 55–72% SiO_2. TTG = tonalite, trondhjemite, and granodiorite.

Marianas Arc than the Costa Rican Arc. The average crustal thickness of the modern arc is also relatively thin, ~18 km (Calvert et al., 2008) and thus not a true representative of continental crust.

Plutonic rocks have been reported in several islands along the Aleutians Arc. Calc-alkaline intrusive rocks in Hidden Bay, Adak (36–31 Ma, Citron et al., 1980), Kagalaska (~13–14 Ma, Citron et al., 1980; Jicha et al., 2006), Amatignak (~31–30 Ma), Ilak (~12 Ma), and Atka Islands (~39–9 Ma, Cai et al., 2015), and granodiorites/tonalites from Medny in the Komandorsky Islands (~12–8 Ma, Tsvetkov, 1991). Kay

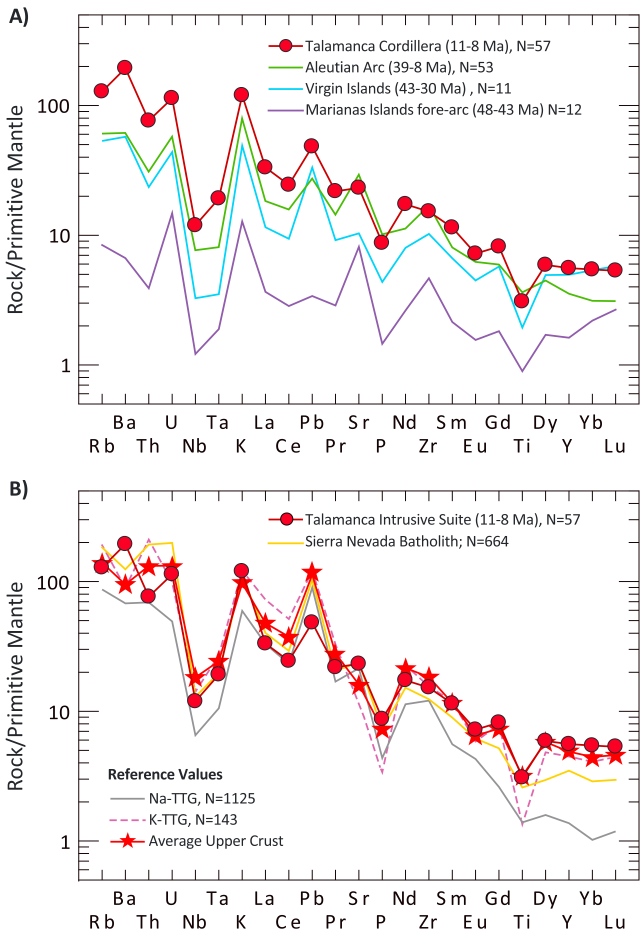

Figure 12. Global comparison of average trace element data (for samples SiO_2 = 55–72%) of the Talamanca intrusive rocks, other arc plutonic rocks. (a) Average composition of Talamanca intrusive rocks compared with Aleutians, Marianas, and Virgin Islands. (b) Average composition of Talamanca intrusive rocks compared with Sierra Nevada batholith and reference compositions of sodic (Na) and potassic (K) TTGs (Moyen, 2011) and Upper Continental Crust (Rudnick & Gao, 2003). The number of samples (N) includes all samples used to calculate the average; however, not all the elements displayed are available in all the analyses (e.g., Rb is more commonly reported than Dy). Complete data references in Figure 11. TTG = tonalite, trondhjemite, and granodiorite.

et al. (1990) proposed two explanations for the silicic calc-alkaline plutons from Adak and Kalkaska Island silicic: melting and assimilation of preexisting Aleutian crust or fractional crystallization of basaltic magmas leaving an amphibole-rich residue. In central and eastern Aleutians, the primitive magmas are mainly basalts, while in the western Aleutians they are mainly andesites (Kay & Kay, 1994; Kelemen, Yogodzinski, et al., 2003; Yogodzinski & Kelemen 1998). Partial melting of subducted oceanic crust in eclogite facies, with subsequent reaction of these melts with peridotite from the mantle wedge, could be the origin for some primitive andesites found in the western Aleutians (Kay, 1978; Kelemen, Yogodzinski, et al., 2003); this contribution from a slab melt end-member is more evident in the Komandorsky Islands in Western Aleutians (Kelemen, Yogodzinski, et al., 2003; Yogodzinski et al., 1995). More recently, obtained isotopic evidence suggests that in central and eastern Aleutians, tholeiitic, and calc-alkaline magmas represent distinct magma sources (Cai et al., 2015), possibly reflecting variable amounts of subducted material in the two series. Therefore, a combination of subducted slab input in the form of a melt (Kelemen, Yogodzinski, et al., 2003) and the subsequent fractional crystallization of the arc primary magmas (Kay et al., 1990; Kay & Kay, 1994), yielded a composition very close to upper continental crust (Kay et al., 1990, and data in Figure 12a), but still not as enriched as the Talamanca suite (Figure 12a). The crustal thickness along the Aleutian arc is relatively thick ~35–40 km (Holbrook et al., 1999; Janiszewski et al., 2013; Van Avendonk et al., 2004). *P* wave velocities range from 4.3 to 7.7 km/s (Holbrook et al., 1999; Van Avendonk et al., 2004). The fastest *P* wave velocities, between 15- and 35-km depths (6.5–7.7 km/s), similar to the Costa Rican section that was described in section 5.3.

The Virgin Islands plutonic rocks (43–30 Ma) are even less enriched than the Talamanca and Aleutian plutons (Figure 12a). Intrusive rocks of this batholith became progressively “more continental” through time (Schrecengost, 2010), but these rocks still did not reach upper crust crustal or TTG compositions. The crustal thickness for the Virgin Islands is estimated to be 30–35 km (Case et al., 1990), making this location together with the Western Aleutians, transitional in terms of crustal thickness and composition between the Marianas and Costa Rica.

The Sierra Nevada Batholith [Figure 12b] is part of a ~35-km-thick (Fliedner et al., 2000), 43-km-wide batholith (Das & Nolet, 1998; Fliedner et al., 1996), just on the border of the Western North America cratonic zone and therefore did not develop on-top of older cratonic material (Driver et al., 2000). The origin of the Sierra Nevada Batholith has been related to deep crustal processes (Cecil et al., 2012; Ducea, 2001; Ratajeski et al., 2005; Reid et al., 1983), a subduction modified mantle source with unclear participation of the lower crust (Coleman & Glazner, 1997; Wenner & Coleman, 2004), or a mixture of mantle and crustal components (Gray et al., 2008). Coleman and Glazner (1997) suggested that (1) the chemical and isotopic characteristics of the highest production peak in the Sierra Nevada Batholith were inherited from the mantle source by melting of high alumina basalts and (2) the compositions do not necessarily reflect interaction with the overlying crust, as there is little evidence that preexisting continental crust was involved in the generation of central Sierra Nevada Batholith (Wenner & Coleman, 2004). An alternative interpretation is that lower crust melting was directly involved in the genesis of the plutonic suite (Frey et al., 1978; Cecil et al., 2012; Coleman et al., 2012; i.e., when the batholith was emplaced it melted the lower crust and developed a dense root that was subsequently lost by delamination; Ducea, 2001; Fliedner et al., 2000). The Talamanca plutonic rocks and Sierra Nevada Batholith have very similar trends in terms of major (Figure 11) and trace elements (Figure 12) with exception of the heavy rare earth element being slightly more enriched in the Talamanca. The crust to the south of Sierra Nevada Batholith have a *P* wave velocity of 5.9–6.3 km/s, suggesting an overall felsic composition representative of continental crust (Fliedner et al., 2000).

In summary, the Talamanca and Sierra Nevada are closer to upper continental crust, the Aleutians and the Virgin Islands suites have transitional values, and the Marinas plutonic rocks are clearly not representative of processes that result in continental crust. The Talamanca, Aleutians, and Sierra Nevada examples also share some clear similarities with Archean TTG, with one important exception, modern plutonic rocks are more potasic than the TTG (Figure 11). The higher K contents of the arc-related samples can be related with more availability of K-bearing sources in modern subduction zones (subducting clays and altered minerals) compared to the Archean, variations of degree of partial melting of the primary magma (e.g., depletions in K due to high degree of mantle melting) or even the loss of K during metamorphic reactions of the Archean TTG suites. A melt component from a mafic protolith (eclogite) is the common denominator to explain the geochemical signatures akin to upper continental composition in the Talamanca, Sierra Nevada, and the Aleutians, and therefore melting of the subducting slab and/or the lower crust in a plate tectonics framework (Subduction Model) is probably a necessary process to generate juvenile continental crust. In the case of the Talamanca Cordillera, this component was generated from melting enriched subducting Galapagos tracks that resulted in some of the most enriched arc magmas globally, whereas melting of depleted “normal” oceanic crust in the Aleutians resulted in transitional compositions, distinctly more enriched in incompatible elements than the Marianas, but not as “continental” as the Talamanca Cordillera plutonic rocks.

7. Conclusions

Melts preserved as intrusive suites from the Talamanca Cordillera record the transition from a depleted oceanic arc to a juvenile continental arc (reaching average upper crust and comparable with Archean TTG compositions). The change in geochemical signature of these rocks is associated with the input from the subducting Galapagos hotspot tracks.

Seismic velocities along the modern arc in Costa Rica compared with other active arcs and average continental crust suggest an intermediate composition beneath the active arc in Costa Rica, closer to global continental crust estimates.

Based on the global comparison with other arc-related intrusive suites and Archean cratons, the Talamanca plutonic rocks show more affinities with continental arcs (Sierra Nevada) or cratonic igneous complexes rather than other modern oceanic arc settings.

A melt component from a mafic protolith (eclogite) is the common denominator to explain the geochemical signatures analogous to upper continental crust estimates in the Talamanca, Sierra Nevada, and the Aleutians. In the particular case of the Costa Rican example, melting of an enriched component (Galapagos tracks) in the subducting slab is a requirement to obtain the compositions intrinsic to juvenile continental crust.

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