frontiers in Earth Science

HYPOTHESIS AND THEORY
published: 08 May 2018
doi: 10.3389/feart.2018.00050

The Evolution of Galápagos Volcanoes: An Alternative Perspective

Karen S. Harpp[1]* *and Dennis J. Geist*[1,2]

[1] Department of Geology, Colgate University, Hamilton, NY, United States, [2] Division of Earth Sciences, U.S. National Science Foundation, Alexandria, VA, United States

The older eastern Galápagos are different in almost every way from the historically active western Galápagos volcanoes. Geochemical, geologic, and geophysical data support the hypothesis that the differences are not evolutionary, but rather the eastern volcanoes grew in a different tectonic environment than the younger volcanoes. The western Galápagos volcanoes have steep upper slopes and are topped by large calderas, whereas none of the older islands has a caldera, an observation that is supported by recent gravity measurements. Most of the western volcanoes erupt evolved basalts with an exceedingly small range of Mg#, La_n/Sm_n, and Sm_n/Yb_n. This is attributed to homogenization in a crustal-scale magmatic mush column, which is maintained in a thermochemical steady state, owing to high magma supply directly over the Galápagos mantle plume. In contrast, the eastern volcanoes erupt relatively primitive magmas, with a large range in Mg#, La_n/Sm_n, and Sm_n/Yb_n. These differences are attributed to isolated, ephemeral magmatic plumbing systems supplied by smaller magmatic fluxes throughout their histories. Consequently, each batch of magma follows an independent course of evolution, owing to the low volume of supersolidus material beneath these volcanoes. The magmatic flux to Galápagos volcanoes negatively correlates to the distance to the Galápagos Spreading Center (GSC). When the ridge was close to the plume, most of the plume-derived magma was directed to the ridge. Currently, the active volcanoes are much farther from the GSC, thus most of the plume-derived magma erupts on the Nazca Plate and can be focused beneath the large young shields. We define an intermediate sub-province comprising Rabida, Santiago, and Pinzon volcanoes, which were most active about 1 Ma. They have all erupted dacites, rhyolites, and trachytes, similar to the dying stage of the western volcanoes, indicating that there was a relatively large volume of mush beneath them. The paradigm established by the evolution of Hawaiian volcanoes as they are carried away from the hotspot does not apply to most archipelagos.

Keywords: ocean islands, hotspot, Galápagos Islands, caldera, petrology, igneous geochemistry, magma supply

OPEN ACCESS

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Correspondence:
Karen S. Harpp
kharpp@colgate.edu

Specialty section:
This article was submitted to Volcanology, a section of the journal Frontiers in Earth Science

Received: *14 January 2018*
Accepted: *18 April 2018*
Published: *08 May 2018*

Citation:
Harpp KS and Geist DJ (2018) The Evolution of Galápagos Volcanoes: An Alternative Perspective. Front. Earth Sci. 6:50. doi: 10.3389/feart.2018.00050

INTRODUCTION

Volcanoes of the Galápagos Islands exhibit remarkable diversity in morphology, eruptive behavior, and magmatic composition. Existing models for the evolution of ocean island volcanoes such as those of Hawaii (e.g., Macdonald et al., 1983; Clague and Dalrymple, 1987, 1988; Walker, 1990) and the Galápagos (e.g., McBirney and Williams, 1969; White et al., 1993; Geist et al., 2014) attribute differences in lava composition and eruptive behavior along the island chain to the location of each volcano relative to the mantle plume. In Hawaii, for example, tholeiitic basalts are effusively erupted during the high-flux, shield-building phase, and alkalic magma is produced in the post-shield phase, when magma supply is waning (e.g., Walker, 1990). Such models assume a progressive evolution in a volcano's eruptive products, directly correlated to the distance between the volcano and the plume, and therefore the volcano's age.

In the Galápagos Archipelago, there is a dichotomy between the younger, western volcanic province and the older, eastern province, with distinct differences in structural features, lithospheric fractionation conditions, and melt generation processes (**Table 1**). Among the most striking variations is the prevalence of large calderas up to several kilometers across and several hundred meters deep on the young western shield volcanoes, contrasting with the older eastern volcanoes, which lack calderas or any morphological evidence of them (**Figures 1**, **2**). On the basis of a synthesis of published geochemical, geologic, and geophysical data, we propose that the Galápagos volcanoes do not follow a consistent evolutionary trend but instead require an alternative to the progressive Hawaiian evolutionary model. We hypothesize that the eastern volcanoes are not an evolved stage of the young western volcanoes but instead formed by a different constructional mechanism controlled by the proximity of the Galápagos Spreading Center (GSC) 1–3 Ma.

TECTONIC SETTING OF THE GALÁPAGOS

The Galápagos Islands are the manifestation of a mantle plume located ∼1,000 km off the west coast of Ecuador, on the Nazca Plate, which is moving eastward at 51 km/my relative to the hotspot (Argus et al., 2011). The east-west striking GSC is 250 km north of Fernandina Island, and is offset at ∼90°50′W by a ∼100 km transform fault (the Galápagos Transform Fault, GTF; **Figure 1**). The GSC is currently migrating away from the archipelago at 47 km/my to the northeast (55°, the difference between the GSC half-spreading velocity and absolute motion of the Nazca plate), progressively increasing plume-ridge distance. On the basis of magnetic data collected across the northern Galápagos seafloor, Mittelstaedt et al. (2012) determined that the GSC has jumped southward at least twice, once ∼2.5–3.5 Ma and again ∼1 Ma, resulting in a current plume-ridge separation of 145–215 km.

COMPARISON OF THE WESTERN AND EASTERN GALÁPAGOS VOLCANOES

Geology and Ages of the Volcanoes

The western Galápagos volcanoes are the youngest in the archipelago (**Figure 1**), owing to the eastward motion of the Nazca plate. Fernandina is the westernmost and youngest island, hosting a single shield. Cosmogenic helium exposure ages led Kurz et al. (2014) to estimate that Fernandina emerged ∼32 ka and has been entirely resurfaced in the last 4.3 ka. Isabela Island consists of 6 separate shield volcanoes, Cerro Azul, Sierra Negra, Alcedo, Darwin, Wolf, and Ecuador, which are connected by land bridges formed from lava flows. Most lavas from the western Galápagos are too young for age determinations using radiogenic argon; all are normally polarized, and Geist et al. (2014) estimate that the oldest ones emerged <500 ka.

The major islands of the eastern Galápagos Archipelago are Santiago, Pinzón, Rábida, Santa Cruz, Floreana, San Cristóbal, Santa Fe, and Española (**Figure 1**). The oldest are San Cristóbal (oldest recorded ages to date are 2.33 ± 0.04 and 2.35 ± 0.03 Ma; White et al., 1993), and Española (2.61 ± 0.11 and 2.71 ± 0.36 Ma; White et al., 1993). Santa Cruz has lavas that span the range from 1.6 Ma to 30 ka (White et al., 1993; Schwartz, 2014). Similarly, Floreana Island lava ages vary from 1.63 Ma to 26 ka (Bow and Geist, 1992; White et al., 1993; Harpp et al., 2014). The limited age data from Santa Fe Island vary from 0.72 ± 0.09 to 2.76 ± 0.06 Ma (White et al., 1993). Rábida's lavas range from 1.03 ± 0.05 to 0.92 ± 0.09 Ma, similar to those from Pinzón, which have ages between 1.4 ± 0.08 and 0.93 ± 0.14 Ma (Swanson et al., 1974; White et al., 1993). Santiago is the youngest of the

TABLE 1 | Compilation of geologic, geophysical, and geochemical differences between the western, eastern, and intermediate volcanoes.

Attribute	Parameter	Western volcanoes	Intermediate volcanoes	Eastern volcanoes
Profile	Morphology	Steep flanks	Shallow slopes	Shallow slopes
Caldera	Morphology	Yes	Perhaps buried	Never
Gravity signal	Gravity	∼30 mg high	unknown	No detectable Bouguer Anomaly
Hydrovolcanism	Tuff cones and rings	Caldera and shorelines	Low elevations only	Low elevations only
Fissure systems	Morphology	Circumferential and radial	Linear; tectonic control	Linear; tectonic control
Faults	Geology	Related to calderas	Rare or absent	Tectonic and abundant
Ages	Geochronology	<0.5 Ma	Most 0.5–1 Ma	Most 1–3 Ma
Eruptive style	Deposits	Mostly lava	Silicic pyroclastic deposits and dome	Intense Strombolian + lavas
Crustal evolution	Mg# variation	Fractionated and buffered	Extensive fractionation	Widely variable cooling histories
Depth of melting	Sm/Yb	D_{top} = 56–58 km	51–57 km	51–53 km
Extent of melting	$\Delta La_n/Sm_n$	Consistent	Consistent	Widely variable
Homogenization	Mg#, Sm/Yb, and $\Delta La_n/Sm_n$	Well-mixed	Poorly mixed	Independent magma batches

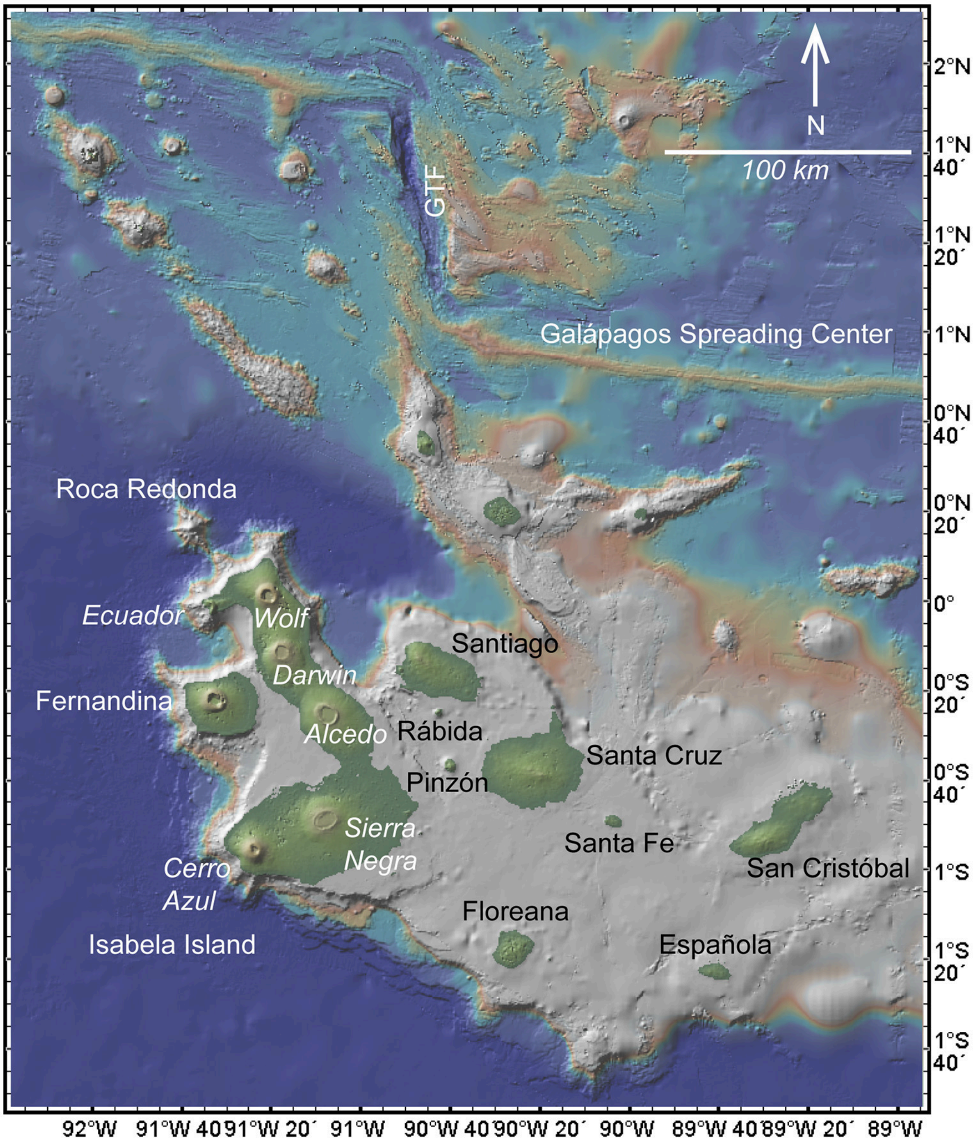

FIGURE 1 | Map of the Galápagos Islands and surrounding bathymetry. Plate motion is almost directly east (51 km/my; Argus et al., 2011). Bathymetric data are from Geomapapp (Ryan et al., 2009). The western volcanoes are labeled in white, those of the intermediate and eastern province in black. GTF, Galápagos Transform Fault.

eastern volcanoes, with only normally polarized lavas and an oldest recorded age of 770 ± 12 ka (Swanson et al., 1974), as well as historical activity, including an eruption in 1906 (Siebert et al., 2011).

Volcano Morphology and Eruptive Fissure Pattern

Western volcanoes

McBirney and Williams (1969) originally described the shapes of the western Galápagos shields as having "overturned soup bowl" profiles (**Figure 2A**). The lower and uppermost flanks are shallow, but mid-flank slopes are significantly steeper, a shape that has been attributed to the distinctive eruptive fissure pattern of the volcanoes (e.g., Rowland, 1996). The western Galápagos volcanoes have circumferentially oriented eruptive fissures around their summits, which shift to radial down the flanks (**Figure 2C**; McBirney and Williams, 1969; Chadwick and Howard, 1991). On the basis of numerical modeling results, Chadwick and Dieterich (1995) attributed this pattern to stresses generated by construction of the edifice plus the influence of a pressurized diapir-shaped magma reservoir; finite element models show that caldera decompression also contributes to the state of stress and fissure orientation (Corbi et al., 2015). A cycle develops, in which the formation of radial dikes establishes conditions for subsequent generation of circumferential dikes, the formation of which encourages initiation of radial dikes, an alternating pattern exhibited by Fernandina's eruptive activity over the past few decades (e.g., Chadwick et al., 2011; Bagnardi and Amelung, 2012; Bagnardi

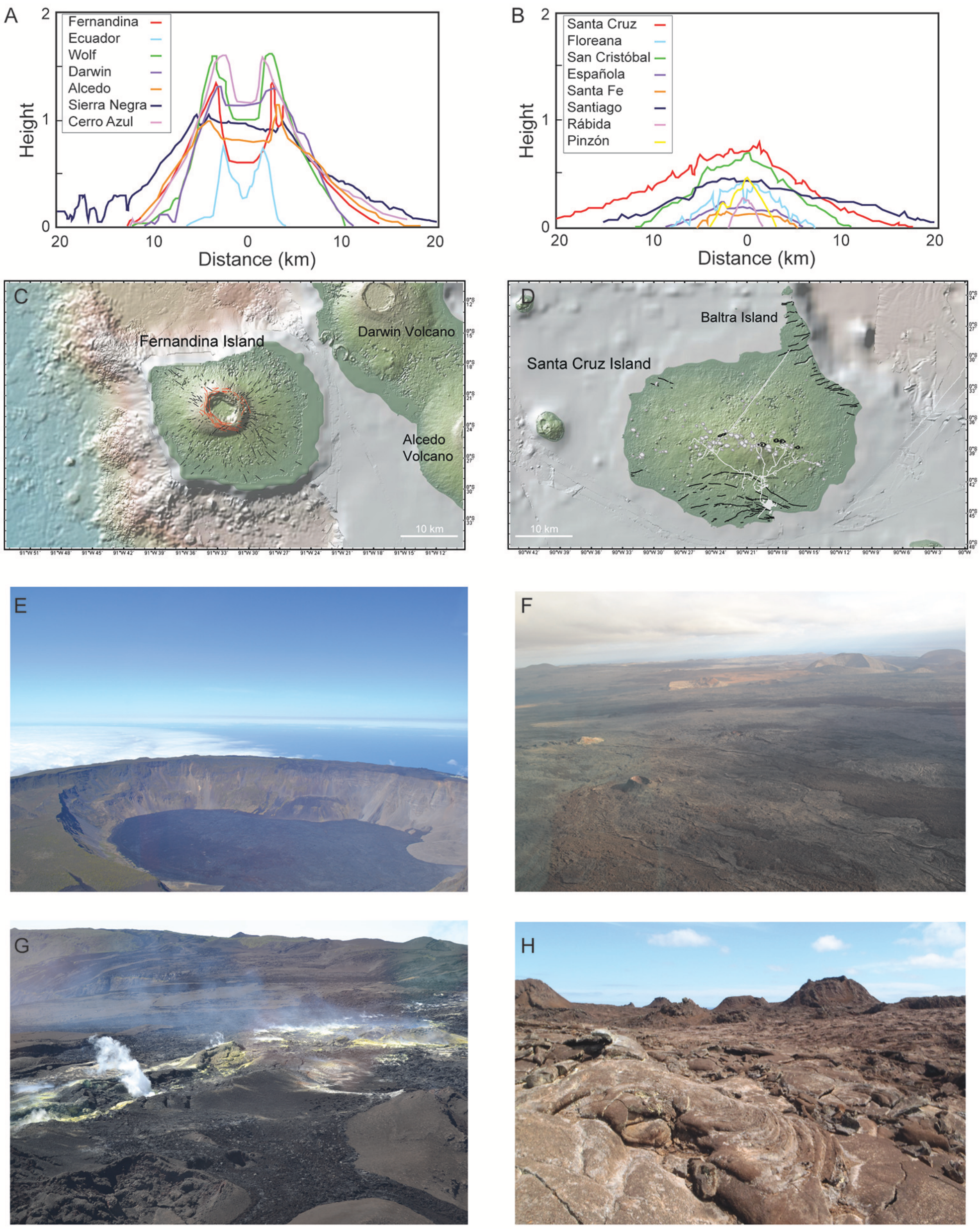

FIGURE 2 | Geomorphic comparison of western and eastern Galápagos volcanoes. **(A)** Profiles of western volcanoes (data from Google Earth). Note prevalence of calderas on all the volcanoes. **(B)** Profiles of eastern volcanoes (data from Google Earth). Note lack of calderas. **(C)** Map of Fernandina Island showing radial (black) and circumferential (red) faults after Chadwick and Howard (1991). Base map from Geomapapp (Ryan et al., 2009). **(D)** Map of Santa Cruz Island showing faults (black) and cinder cones (gray circles) (structural features mapped by Schwartz, 2014). Roads are also shown (gray). Base map from Geomapapp (Ryan et al., 2009). **(E)** Aerial view of the Wolf Volcano caldera. **(F)** Aerial view of NE Santiago Island. **(G)** Aerial view of site of 2015 eruption of Wolf Volcano along circumferential fault at summit. Caldera is to the left in the image. **(H)** Ground-level view of fissures in young volcanic province of San Cristóbal Island. Photo credits: K. Harpp.

et al., 2013). As initially observed by Simkin et al. (1973), short lava flows are erupted from the circumferential fissures that ring the volcano summits, constructing the steep upper slopes of the western shields (Chadwick and Howard, 1991). The transition from circumferential to radial fissures occurs at the break in slope down the flanks, from which longer flows emanate to build the shallower lower flanks (Chadwick and Howard, 1991). Recent geodetic evidence suggests that individual dikes actually twist 90° as they intrude from the summit platform to the lower flanks (Bagnardi et al., 2013).

The submarine environment in the western Galápagos is dominated by flat lying sheet flows and focused rifts that emanate from the subaerial structures (**Figures 1**, **2C**) but relatively few small seamounts, and there is no submarine Loihi-like edifice growing at the leading edge of the hotspot track. The sheet flows are stacked in terraces that define the western edge of the Galápagos Platform (Geist D. et al., 2008). The submarine rift zones are well-developed on the flanks of Fernandina, Cerro Azul, Ecuador, Wolf, and Darwin Volcanoes (**Figure 2C**; Geist D. J. et al., 2006).

Eastern volcanoes

The older, eastern Galápagos Islands have strikingly different morphologies from the western shields, with greater variability in size and shape (**Figures 1**, **2B**). For example, Santa Cruz is 40 km across (larger than Fernandina at ∼30 km), whereas Santa Fe is only 7 km in diameter. Santiago, San Cristóbal, Santa Fe, and Española are notably elongate, compared to the more circular shapes of Floreana and Santa Cruz. The eastern islands also have lower summits and more consistently shallow slopes than the western shields (**Figure 2B**).

Several eastern islands, particularly those with more elongate shapes, exhibit structural alignments of eruptive cones, pit craters, fissures, and faults; there is no evidence of the circumferential or radial fissure structures that are observed on the western shields (e.g., Chadwick and Howard, 1991). On Santa Cruz, a WNW-trending alignment of scoria cones and pit craters stretches across the island, as well as two sets of E-W/ENE oriented faults that formed in distinct episodes, one no later than ∼1.16 Ma, and the second between 40 and 270 ka (Schwartz, 2014; **Figure 2D**). Eruptive activity along the cross-island fissure system coincided with the initiation of the E-W oriented faults on the southern flank of Santa Cruz (**Figure 2D**; Schwartz, 2014). San Cristóbal, which consists of two smaller shield volcanoes, has a set of ENE-striking faults that are parallel to eruptive cone alignments, particularly in the youngest lava province (Geist et al., 1986; Mahr et al., 2016). Floreana's abundant cinder cones are also arranged in an ENE-striking swath that crosses the island (Harpp et al., 2014). Many fissures on Santiago are parallel to the elongation of that island (Swanson et al., 1974). The E-W faults that cross-cut Santa Fe and Española Islands have resulted in the formation of a series of horst and graben structures across the islands (Hall, 1983; Geist et al., 1985).

The submarine environment in the eastern Galápagos is not as extensively mapped as that in the west, but recent research expeditions (e.g., Schwartz et al., 2017) have identified clusters of monogenetic seamounts off the coasts of Santiago, Santa Cruz, and Floreana Islands. Despite limited high resolution bathymetric surveys, neither structures comparable to the western terraces (Geist D. et al., 2008) nor large submarine rift zones (e.g., Geist D. J. et al., 2006) exist in the eastern archipelago.

Eruptive Style

Western volcanoes

The eruptive style of the western shields is predominantly effusive, generally beginning with Hawaiian-style lava fountaining either along circumferential fissures near the caldera rim or radial fissures on the flanks (e.g., Teasdale et al., 2005; Geist D. J. et al., 2008; **Figures 2C,E,G**). A Strombolian phase can follow the lava fountaining once the eruption has focused to a few active vents (e.g., Geist D. J. et al., 2008). Eruptions that have been observed (including Fernandina in 2017, 2009, 2005, 1995; Wolf in 2015; Sierra Negra in 2005, 1979; Cerro Azul in 2008) have been relatively short in duration, ranging from days (Fernandina, 6 days in 2017) to weeks (Cerro Azul, 5 weeks in 1998, Teasdale et al., 2005; Sierra Negra, 8 weeks in 1979, Reynolds et al., 1995).

Hydrovolcanic activity occurs within the calderas of the western volcanoes, owing to interaction of magma with caldera lakes and caldera-bound aquifers (e.g., Cerro Azul, Naumann and Geist, 2000; Sierra Negra, Reynolds et al., 1995; Fernandina, Simkin and Howard, 1970; Howard et al., in press). Abundant large tuff cones also occur along the shorelines (e.g., Tagus Cove on the western coast of Volcan Darwin) or just offshore (Islas Tortuga and Cowley), as well as a rootless cone fields (e.g., on the flanks of Cerro Azul). The 1968 eruption of Fernandina resulted in a major caldera floor collapse event that was accompanied by explosive phreatomagmatic activity owing to the presence of a lake on the caldera floor (Simkin and Howard, 1970; Howard et al., in press).

Alcedo is the only western shield that has documented Plinian-style activity, having erupted ∼1 km^3 of rhyolitic tephra and lava (dense rock equivalent) ∼100,000 years ago (Geist et al., 1994, 1995). Geist et al. (1995) attribute the explosive behavior and evolved compositions to extensive crystallization of magma reservoirs in systems that are cooling (Geist et al., 2014).

Eastern volcanoes

The largest of the eastern islands have young lavas and protracted periods (>1 million years) of eruptive activity. The smaller volcanoes of Pinzón and Rábida are exceptional, because they went extinct shortly after their peak activity at ∼1 Ma (Swanson et al., 1974). On Santiago, historical activity has been identified on both the eastern and western ends of the island (**Figure 2F**; 1906 C.E. at Sulivan Bay in the east and ∼1754 C.E. at James Bay in the west; Siebert et al., 2011). Floreana's Alayeri cone and associated lavas have a cosmogenic surface exposure age of 26 ± 7 ka (Kurz and Geist, 1999; Harpp et al., 2014). Available age data suggest that although activity at Santiago and Floreana has been waning, it has been continual (Gibson et al., 2012; Harpp et al., 2014), as opposed to rejuvenescent (e.g., Chen and Frey, 1983). To date, no lavas younger than ∼2.5 Ma have been identified on Española, nor does the island host a morphologically young lava field (White et al., 1993; McGuire et al., 2015). Even though there is no obvious morphologically young province on Santa Fe, White et al. (1993) publish a 0.72 Ma age, nearly 2 million years younger than the oldest dated lava from this small island, suggesting a span of activity comparable to that of the larger eastern islands.

Santa Cruz has experienced several eruptive phases. There have been at least two periods of activity, one between 1,620 and 1,160 ka and another lasting from about 700 to 20 ka (Schwartz, 2014), although lavas from the intervening episode may exist beneath the younger cover. San Cristóbal hosts a young lava province, located near the junction between the two shield volcanoes (Geist et al., 1986; **Figure 2H**). These large lava fields were emplaced between 5 and 174 ka, according to cosmogenic helium surface dating (Mahr et al., 2016). The sharp boundary between the young lava province and the rest of the island's more heavily vegetated surfaces suggests that there may have been a hiatus in eruptive activity (Mahr et al., 2016), but there are currently too few age determinations from the main shield volcanoes to be certain. Moreover, older lavas are certainly buried beneath the southwest shield (Geist et al., 1986; White et al., 1993).

Much of the late-stage activity on Santiago, Floreana, Santa Cruz, and San Cristóbal was more explosive than is observed in the western shields. All of the eastern islands are notable for their numerous monogenetic scoria and tuff cones. Effusive eruptions during the late-stage activity are largely from tectonically directed fissures (Geist et al., 1986; Bow and Geist, 1992; Gibson et al., 2012; Wilson, 2013; Harpp et al., 2014; Schwartz, 2014; McGuire et al., 2015; Mahr et al., 2016; Pimentel et al., 2016). For instance, the youngest San Cristóbal lavas emanate from sets of aligned cones that parallel the ENE-trending faults along the north coast and elongation of the island (**Figure 2H**; Geist et al., 1986; Mahr et al., 2016). Similarly, the most recent eruptive activity on Santa Cruz was localized along an E-W trending summit vent system of cinder cones (Bow, 1979; Schwartz, 2014; **Figure 2D**).

Floreana, Santiago, San Cristóbal, Pinzón, and Rábida volcanoes have erupted with sufficient energy that they have transported mafic and ultramafic xenoliths to the surface (McBirney and Williams, 1969; Baitis and Lindstrom, 1980; Geist et al., 1986; Lyons et al., 2007; Bercovici et al., 2016). In most cases, xenoliths tend to be found at tuff-cones and scoria-rich vents (especially the older vents on Floreana, Bow and Geist, 1992; Lyons et al., 2007; Harpp et al., 2014; Rábida, Bercovici et al., 2015, 2016). A rhyodacitic ignimbrite deposit is exposed on the northeast coast of Rábida Island, the only evidence of explosive silicic volcanism found to date in the eastern Galápagos.

Despite being small compared to the major eastern Galápagos volcanoes, Española embodies many of the characteristics common to those volcanoes, including E-W trending faults and abundant scoria and tuff cones. Most of the monogenetic vents are located along the northern coast of the island, whereas the southern coast consists of steep cliffs that expose nearly horizontally stacked, 1–5 m thick lava flows (McGuire et al., 2015), some of which bury a single scoria cone (Hall, 1983). Given the volcano's small area and these observations, Española may be the remnant of a larger structure that experienced sector collapse or extensive wave erosion of its southern half.

Calderas (and Lack Thereof)

Western-volcanoes

The most striking geomorphic feature of the western shields is the large caldera at the summit of each volcano (**Figures 1**, **2A,C,E**). All of the young western shield volcanoes (with the exception of Roca Redonda, which does not lie on the Galápagos Platform; Standish et al., 1998; **Figure 1**) are endowed with major calderas, which can be classified in two morphological groups. Sierra Negra, Alcedo, and Darwin volcanoes on Isabela Island have shallow, wide calderas, similar to those of Mauna Loa and Kilauea, Hawaii (Poland, 2014). For example, the Sierra Negra caldera has a diameter of about 9 km and is about 100 m deep. In contrast, the calderas of Wolf (**Figure 2E**), Cerro Azul, and Fernandina volcanoes are narrower and deeper, typically ∼5 km in diameter and 600–1,000 m deep (e.g., Munro and Rowland, 1996). All of the calderas have complex structural histories of multiple collapses and refilling events (e.g., Reynolds et al., 1995; Poland, 2014), making it difficult to correlate caldera to with magma supply in a straightforward manner. For example, Sierra Negra, which erupted most recently in 2005 (Geist D. J. et al., 2008), is shown to cyclically inflate, fault, and subside in less than a decade (Chadwick et al., 2006).

Gravity surveys conducted at Fernandina and Sierra Negra volcanoes detect well-defined, localized Bouguer gravity highs reaching ∼30 mGal over the centers of the calderas (Ryland, 1971; Case et al., 1973; Geist D. et al., 2006; Vigouroux et al., 2008). As is the case for similar signals observed over Hawaiian volcanoes (50–100 mGal; Kinoshita, 1965; Flinders et al., 2013), the elevated gravity anomalies have been attributed to dense (predicted sub-surface densities higher by ∼600 kg/m^3), residual cumulate bodies beneath the calderas.

Eastern volcanoes

The major eastern islands lack large calderas (**Figures 2B,D,F**). Pinzón has a small (∼1,500 m diameter) caldera near the summit (Baitis and Lindstrom, 1980), and a sequence of arcuate faults may be remnants of a filled caldera at Rábida (Bercovici et al., 2015, 2016).

In contrast to the ∼30 mGal Bouguer Anomaly (BA) highs detected at Fernandina and Sierra Negra calderas (Case et al., 1973; Vigouroux et al., 2008), recent gravity surveys reveal variations of only ± ∼6 mGal on Santa Cruz and ± ∼3 mGal on San Cristóbal's southern edifice (Cleary et al., in review), indicating that there are no dense cumulate bodies underlying either island.

Compositional Observations

It has been long recognized that the eastern and western Galápagos Archipelago define fundamentally different volcanic and petrologic provinces (McBirney and Williams, 1969). The compositional variation is summarized here by examining parameters governed by extent of lithospheric fractionation, depth of melt generation, and extent of melting.

Shallow Fractionation

Western volcanoes

Geist et al. (2014) used magnesium number (Mg# = molar [MgO/(MgO + FeO)]*100) as a metric to document the thermal conditions of the magma reservoirs supplying each of the young western shield volcanoes. Mg# is a strong function of the extent of olivine and pyroxene crystallization but is not affected by plagioclase accumulation, thereby providing an estimate of magmatic temperature; Geist et al. (2014) calculated that for every 3.6°C of cooling, Mg# decreases by 1. To characterize the extent of fractionation at each volcano, we use the methods of Geist et al. (2014), who produced Gaussian kernel density distributions (Rudge, 2008; Wessa, 2015) of Mg#. We interpret the maximum density (MD) for each volcano as an indicator of average extent of fractionation and the inter-quartile range (IR) as a measure of temperature variation (**Figures 3**, **4A**). The western Galápagos shield volcanoes have Mg# MD values from a high of 56.3 ($n = 60$) at Cerro Azul to a low of 39.9 ($n = 22$) at Alcedo volcano, which has produced the most evolved magmas in the archipelago.

Geist et al. (2014) divided the western shields into two categories on the basis of their inter-quartile ranges (**Figures 3**, **4A**). "Monotonous" volcanoes include Fernandina, Wolf, and Darwin volcanoes. "Diverse" volcanoes, in contrast, erupt lavas with a greater range of temperatures and in the Geist et al. (2014) classification, included Cerro Azul, Alcedo, Sierra Negra, and Ecuador. On the basis of our analysis, which includes all published data from the western shields (**Figure 3**), Fernandina and Darwin volcanoes exhibit the least variation in Mg#, with an IR of 3.4. Wolf, Ecuador, and Sierra Negra volcanoes are close, extending to an IR of 5.1 for Sierra Negra. The real distinction comes for Cerro Azul and Alcedo, which exhibit considerably more variation than the other western shields, with IRs of 10.3 and 30.7. Thus, we suggest a minor adjustment to the Geist et al. (2014) classification; "Monotonous" volcanoes are Fernandina, Darwin, Wolf, Ecuador, and Sierra Negra, whereas only Cerro Azul and Alcedo are considered "Diverse," but of course there is likely a spectrum of compositional variation.

Eastern volcanoes

The average composition of every major eastern Galápagos volcano is significantly more primitive than any of the western shields (**Figures 3**, **4A**). Floreana, San Cristóbal, Española, and Santa Cruz all erupt lavas with relatively high Mg#s, with MDs from 63.2 ($n = 120$; Santa Cruz) to 70.0 ($n = 181$; Floreana). Santiago lavas yield an MD of 59.4 ($n = 60$) and Santa Fe's MD is 50.1 ($n = 10$), intermediate between typical eastern and western volcanic extents of fractionation. Rábida and Pinzón, both of which have produced silicic lavas comparable to those erupted by Alcedo volcano, have correspondingly low MD values of 35.0 ($n = 44$) and 38.0 ($n = 42$).

Furthermore, all the eastern volcanoes exhibit considerably greater variability in their major element compositions than is observed for the "monotonous" volcanoes of the western archipelago (**Figures 3**, **4A**). Floreana (5.9; $n = 181$), San Cristóbal (6.2; $n = 79$), and Española (6.2; $n = 57$) have the least variable Mg# signatures, but their IRs still exceed those of Sierra Negra (5.1; $n = 42$). Santiago has the greatest Mg# variability, with an IR of 21.4 ($n = 60$), between those of Cerro Azul and Alcedo.

Depth of Melt Generation

Western volcanoes

Variations in depth of melting can be examined using the Sm_n/Yb_n (the ratio of chondrite-normalized concentrations) of erupted basalts, owing to fractionation of the heavy rare-earth elements by garnet in an ascending melt column (e.g., Gibson and Geist, 2010). The depth of the garnet-spinel reaction depends on temperature and composition, but is between ∼70 and 90 km for peridotite (Klemme and O'Neill, 2000). In their study of

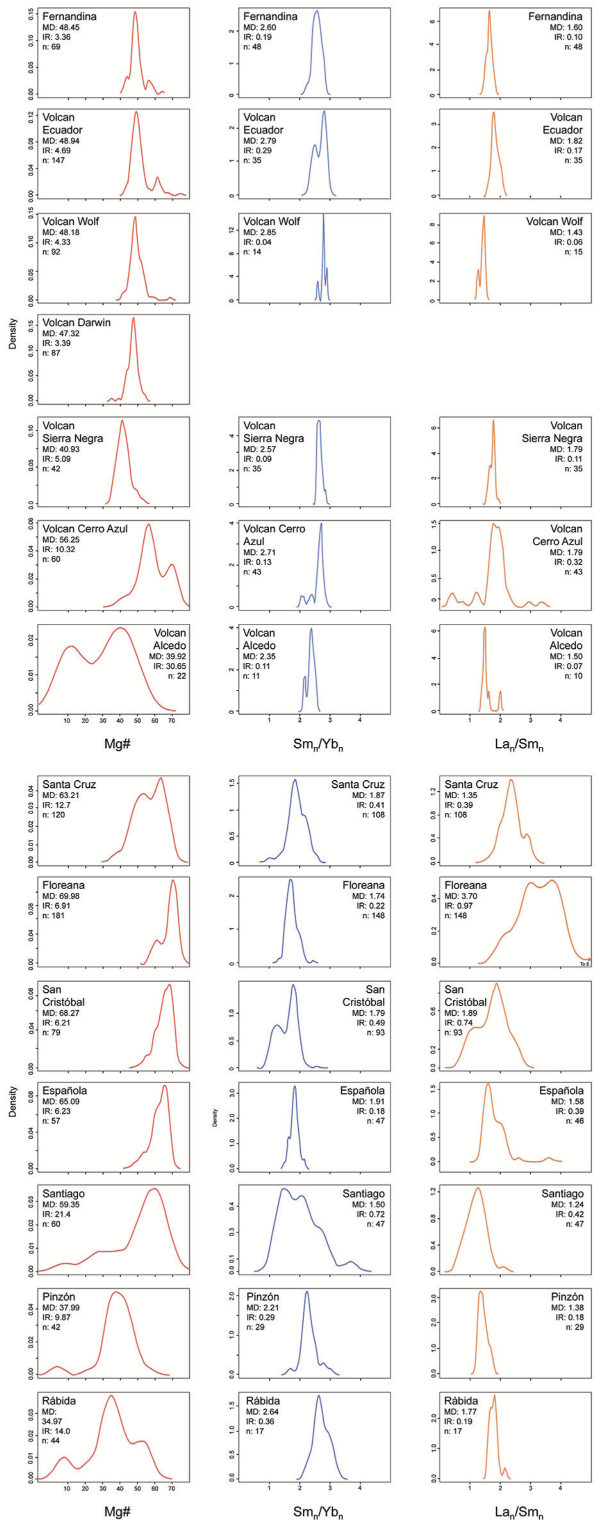

FIGURE 3 | Distributions of Mg#, Sm_n/Yb_n, and La_n/Sm_n variations across the western and eastern Galápagos volcanoes, displayed as probability density functions (generated using Gaussian kernel density estimations; MD, Maximum Density and IR, Interquartile Range). For the Sm_n/Yb_n, and La_n/Sm_n analyses, only samples within MgO > 4 wt.% were included;

(Continued)

FIGURE 3 | all available data were used for the Mg# analyses. Data sources are compilations of downloaded data from PetDB, representing only subaerial samples from the volcanoes, plus unpublished data (unpublished sources: Darwin Volcano data from T. Naumann, pers. comm., 2017; Española data from McGuire et al., 2015; Santa Cruz data from Wilson, 2013; San Cristóbal data from Mahr et al., 2016, and Pimentel et al., 2016). Smoothing bandwidths for Gaussian kernel density estimations were selected automatically using the Sheather and Jones (1991) method. For Mg#s, they range between 0.92 and 7.59 for the western volcanoes, and 0.94 and 2.75 for the eastern volcanoes. For Sm_n/Yb_n, smoothing bandwidths vary between 0.01 and 0.14 for the western volcanoes, and 0.04 and 0.22 for the eastern volcanoes. For La_n/Sm_n, western bandwidths are 0.02–0.10, and eastern values are 0.06–0.32. Slight disagreements between the IR and MD of the western shields from the Geist et al. (2014) calculations are the result of minor differences in the datasets that were used in the two studies. Rare earth element ratios are normalized to chondrite (McDonough and Sun, 1995).

lithospheric thickness beneath the Galápagos, Gibson and Geist (2010) showed that lithospheric thickness (H) can be predicted by the equation:

$$H = 46.57 * (\frac{Sm}{Yb})_n^{0.216}$$

and it ranges from 58 km at Fernandina to 46 km at San Cristobal.

Our synthesis (which includes more analyses from the eastern islands than that of Gibson and Geist, 2010) with MgO > 4% from the western shield volcanoes exhibit higher Sm_n/Yb_n than in the rest of the archipelago, with the lowest values occurring at Alcedo (2.35; $n = 11$) and the highest at Wolf Volcano (2.85; $n = 14$; **Figures 3**, **4B**). Inter-quartile ranges for Sm_n/Yb_n are quite low, indicating relatively little variability in melt generation conditions at each volcano (**Figures 3**, **4B**).

Eastern volcanoes

Most eastern Galápagos magmas have lower Sm_n/Yb_n values than is observed in the western archipelago, indicating shallower average depths of melt generation in the east. Only Rábida has an MD for Sm_n/Yb_n that falls within the range of the western shields (2.64; $n = 17$), and Pinzón's is close with an MD of 2.21 ($n = 29$). Otherwise, in the east, Santiago has the lowest MD of Sm_n/Yb_n (1.50; $n = 47$), whereas Santa Fe has the highest (1.98; $n = 3$; **Figures 3**, **4B**). Individual eastern volcanoes exhibit significantly more variation (IR) in Sm_n/Yb_n and consequently depth to the top of the melt column than is the case for the western shields, particularly the larger islands of Santa Cruz, San Cristóbal, Santa Fe, and Santiago (**Figures 3**, **4B**).

Extent of Melting

Any attempt to use simple incompatible trace element ratios (e.g., La_n/Sm_n) to document extent of melt generation in the archipelago must take into account the complexities imposed by the compositionally distinct mantle reservoirs that contribute to Galápagos magmas. When plotted on an archipelago-wide scale, ε_{Nd} correlates inversely with the lowest La_n/Sm_n from individual volcanoes (**Figure 5**; e.g., White et al., 1993). We attribute this correlation to mixing between mantle sources with different compositions, specifically a depleted mantle source (with low La_n/Sm_n and high ε_{Nd}) and 3 plume components (all with high La_n/Sm_n and low ε_{Nd}); mantle endmember variations in the Galápagos have been documented in numerous regional studies (e.g., White and Hofmann, 1978; Geist et al., 1988; Geist, 1992; White et al., 1993; Harpp and White, 2001). Magmas with higher La_n/Sm_n (those that lie to the higher La_n/Sm_n side of the ε_{Nd}-lowest La_n/Sm_n correlation line on **Figure 5**) then must therefore be the result of lower extents of melting of the mixed source. We define the parameter $\Delta La_n/Sm_n$ as the difference between a rock's measured La_n/Sm_n and the La_n/Sm_n value along the correlation line (**Figure 5**). The $\Delta La_n/Sm_n$ parameter, discussed below, reflects variations in degree of melting, taking into account different source compositions.

Western volcanoes

The average $\Delta La_n/Sm_n$ for western volcano basalts (MgO > 4.0 wt.%) varies from a high of 0.72 ($1\sigma = 0.12$) at Volcan Ecuador to 0.38 ($1\sigma = 0.08$) at Fernandina (**Figure 5**). The two compositionally "diverse" volcanoes, Cerro Azul and Alcedo (e.g., Geist et al., 2014), exhibit the greatest variability in $\Delta La_n/Sm_n$.

Eastern volcanoes

Values of $\Delta La_n/Sm_n$ at San Cristobal, Santa Cruz, Espanola, and Santa Fe are similar to those of the western shields, but Floreana lavas have a dramatically elevated average $\Delta La_n/Sm_n$ compared to the rest of the Galápagos volcanoes (**Figure 5**). Clearly, the $\Delta La_n/Sm_n$ metric may not completely compensate for the extreme incompatible trace element compositions at Floreana, which are attributed to an infusion of ancient recycled ocean crust (e.g., Harpp et al., 2014). Floreana volcano aside, the extent of melting as reflected in $\Delta La_n/Sm_n$ does not vary significantly between the western and eastern Galápagos provinces. In contrast, the *variability* in extent of melt generation is greater in the eastern Galápagos, with standard deviations that mostly exceed those at western volcanoes (**Figure 5**).

DISCUSSION

There is a striking dichotomy between eastern and western Galápagos volcanoes in terms of their age, eruptive flux, volcano morphology, and magma compositions. Two possibilities may explain this systematic difference: either the young lavas of the eastern archipelago overlie western-type volcanoes and are in a later stage of evolution, or the eastern volcanoes have always been different in most fundamental respects.

Three of the eastern volcanoes that have been studied in detail, Santa Cruz, Floreana, and San Cristóbal, have exposed lavas that erupted over 1 million years apart, and in the case of San Cristóbal, the duration of volcanism exceeds 2 million years (Bow, 1979; Geist et al., 1986; Bow and Geist, 1992; Harpp et al., 2014; Schwartz, 2014). Although the geochronological data are insufficient to document the eruptive flux (e.g., Kurz and Geist, 1999), the magmatic flux at all of the eastern islands has been many times smaller than that of the western volcanoes. At all three of the large eastern islands islands, no relationship has been found between the age of eruption and composition. None of these volcanoes is significantly incised by erosion in the arid Galápagos, thus older lavas with different compositions

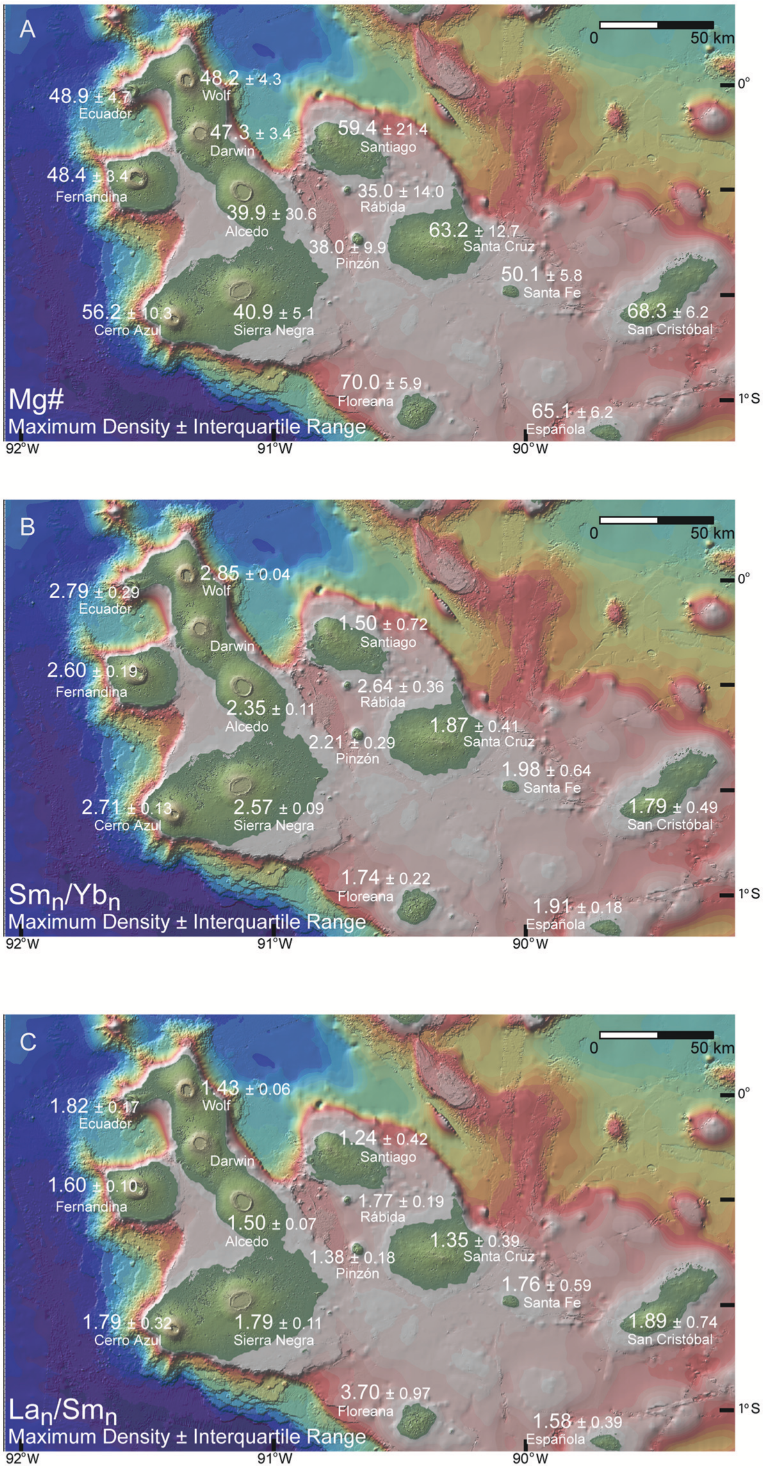

FIGURE 4 | Map views of geochemical and petrologic variations in Galápagos volcanoes (map courtesy of E. Mittelstaedt and Z. Cleary, pers. comm., 2017). MD, Maximum density; IR, Interquartile range; n, number of datapoints used in density calculations (see text for details). Data sources the same as in **Figure 3**. **(A)** Distribution of Mg# in Galápagos volcanoes. Mg# is used as a measure of magmatic temperature and extent of shallow fractionation. **(B)** Distribution of Sm_n/Yb_n variations in Galápagos volcanoes. Sm_n/Yb_n is used as a measure of depth of melting. **(C)** Distribution of La_n/Sm_n variations in Galápagos volcanoes. La_n/Sm_n is used as a measure of extent of melting (see text for details). Rare earth element ratios are normalized to chondrite (McDonough and Sun, 1995).

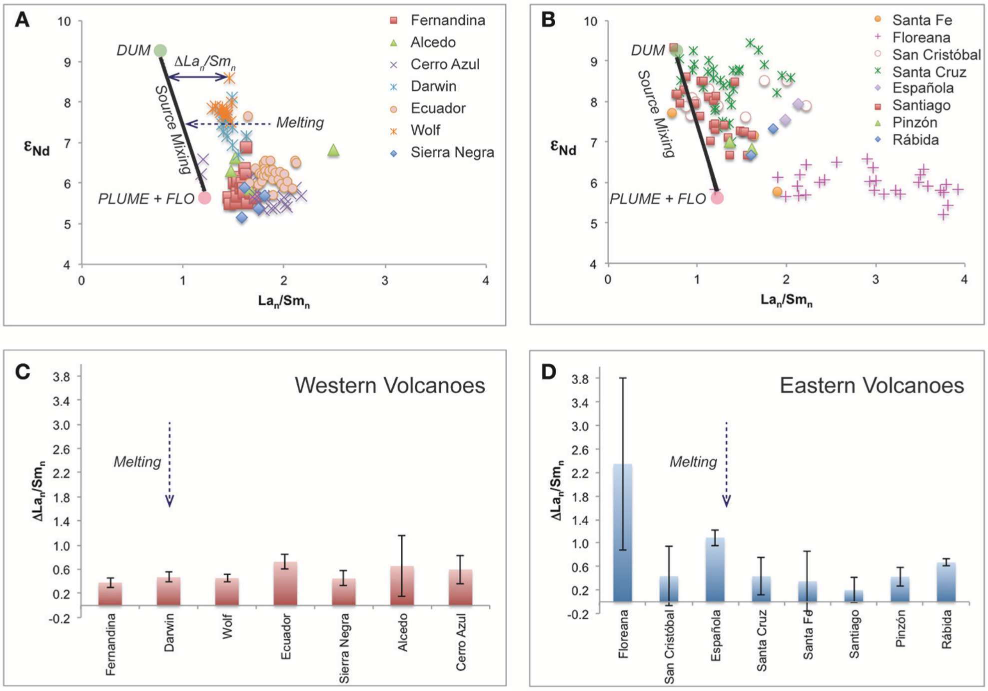

FIGURE 5 | (A) Distribution of ε_{Nd} and La_n/Sm_n in western Galápagos volcanoes. The solid line indicates the relationship between ε_{Nd} and the lowest La_n/Sm_n value across the archipelago. *DUM* is the composition of derived from the depleted upper mantle. PLUME and FLO are the compositions of magmas derived from mantle sources in the Galápagos plume, from Harpp and White (2001). **(B)** Distribution of ε_{Nd} and La_n/Sm_n in eastern Galápagos volcanoes; solid line as in **(A)**. **(C)** $\Delta La_n/Sm_n$ for western Galápagos volcanoes; a graphical representation of the calculation is shown as the double-headed arrow. $\Delta La_n/Sm_n$ is defined as the difference between a rock's measured La_n/Sm_n and the La_n/Sm_n value predicted by the line for the island's average ε_{Nd} shown in **(A)** and **(B)**. The $\Delta La_n/Sm_n$ parameter is interpreted as a measure of variation in extent of melting (as indicated by the dashed arrows), having taken into account different mantle source compositions. Error bars are $\pm 1\sigma$. **(D)** $\Delta La_n/Sm_n$ for eastern Galápagos volcanoes. Error bars are $\pm 1\sigma$. Numbers of samples used for each volcano are: Fernandina (20); Darwin (10); Wolf (13); Ecuador (29); Sierra Negra (4); Alcedo (4); Cerro Azul (19); Floreana (36); San Cristóbal (10); Española (2); Santa Cruz (33); Santiago (25); Pinzón (2); Rábida (2). Only lavas with both ε_{Nd} and La_n/Sm_n data were used in this analysis, from data sources listed in **Figure 3**.

could exist beneath the oldest sampled lavas. Nevertheless, the existing evidence is that the exposed lavas reflect the entire composition spectrum of each volcano. Also, as described below, geophysical observations indicate that the eastern volcanoes do not cap subsided western Galápagos edifices.

Implications of Physical Differences

Physical Structures

The expansive calderas topping the western shields are directly related to large, shallow magma reservoirs, which have been identified by both deformation and seismic studies (Amelung et al., 2000; Geist D. et al., 2006; Tepp et al., 2014). The calderas are multi-cyclical, owing to many episodes of collapse and partial refilling. The exact mechanism between magma evacuation and caldera formation is poorly understood; the only documented caldera collapse was related to a small but explosive eruption at Fernandina in 1969 (Simkin and Howard, 1970; Howard et al., in press). The existence of the calderas is also tied to the active historical record of eruptions at these volcanoes, indicating a strong magma flux.

Further support for robust, long-lived magma reservoirs beneath the western volcanoes comes from gravity studies. The ∼30 mGal Bouguer Anomaly gravity highs detected at Fernandina (Case et al., 1973) and Sierra Negra (Vigouroux et al., 2008) have been attributed to large bodies of dense cumulate bodies. These dense rocks are complements to the relatively evolved eruptive rocks, and development of crustal-wide cumulate bodies has been attributed to steady state magmatic reservoirs with high magma supplies, in order to achieve the conditions necessary to regulate crystallization prior to eruption (e.g., Geist et al., 2014).

Large magma flux, calderas, shallow magma chambers, and the lack of strong tectonic deviatoric stresses contribute to the characteristic morphology of the western Galápagos shields. Stresses imparted by the calderas and the steep slopes overwhelm tectonic influences, leading to nearly symmetrical shapes and the pattern of circumferential fissures near the summit and radial fissures on the lower and submarine flanks (**Figures 2A,C,E**; Chadwick and Howard, 1991; Chadwick and Dieterich, 1995; Geist et al., 2005; Chadwick et al., 2011; Bagnardi et al., 2013).

In marked contrast, the eastern volcanoes lack calderas (**Figures 2B,D**). According to modeling carried out on gravity data from San Cristóbal and Santa Cruz, the small Bouguer Anomaly gravity signals beneath the islands (±∼ 3 mGal on

San Cristóbal, ±∼ 6 mGal on Santa Cruz; Cleary et al., in review) eliminate the possibility of a significant cumulate body underlying the volcanoes. These signals cannot be explained by infilling of older calderas by lava flows (Cleary et al., in review). The authors conclude that neither San Cristóbal nor Santa Cruz ever hosted the long-lived shallow magma reservoir requisite for producing a caldera.

Furthermore, most of the eastern Galápagos volcanoes are elongate, dominated by linear fissures and faults, or have linear rift zones, in contrast to the more symmetrical structures of the western volcanoes. These observations suggest that the eastern volcanoes were supplied by a less robust magma flux. The consistently ∼E-W trending structures across the eastern archipelago also reflect formation in an environment of relatively strong, regional tectonic stress (e.g., Harpp and Geist, 2002; Harpp et al., 2003).

Petrologic Implications

Shallow Fractionation

Most of the western Galápagos volcanoes erupt monotonous suites of lava, with Mg# varying by only a few percent (**Figure 3**), indicating that the magmas erupted within a range of <30°C over the history of the volcano; these are referred to as being in a "steady state" phase (Geist et al., 2014). Moreover, the eruptive lavas tend to be relatively strongly evolved, with Mg# <50. The evolved compositions and their limited variation are the result of thermochemical buffering by a crustal-wide mush column (Geist et al., 2014). The mush column is maintained in a steady state owing to a relatively high magma supply rate, which in turn is reflected by the high eruption rate. The magmas typically equilibrate with their phenocryst assemblage at shallow levels (Geist et al., 1998), consistent with the geophysical evidence of shallow subcaldera magma bodies.

Cerro Azul and Alcedo volcanoes are not in a steady state. Cerro Azul has both the most primitive and most diverse basalt compositions of any volcano in the west (**Figures 3**, **4**). This has been attributed to Cerro Azul being in a juvenile transient phase of magmatism at the leading edge of the hotspot; a crustal-scale mush column has yet to be assembled there. This interpretation is consistent with petrologic (Geist et al., 1998) and geophysical (Amelung et al., 2000) studies, which indicate that Cerro Azul's magma body is deeper than the others in the western Galápagos.

Alcedo is unique among the active western volcanoes because of its rhyolitic eruptions (Geist et al., 1994). Petrologic studies show that the rhyolites result from fractional crystallization within the mush column, which occurs because the volcano has been carried away from the hotspot (Geist et al., 1995). We note that Sierra Negra's magmas are also more evolved than the other western volcanoes (Reynolds and Geist, 1995); it is possible that its mush column is also cooling as it is being carried away from the hotspot, as Cerro Azul receives a progressively more robust magma supply with time.

In almost every compositional parameter, the eastern islands contrast with the western ones (**Figures 3**, **4**). The eastern lavas on the whole are much more primitive, and they have undergone a greater range of cooling and crystallization, as measured by the interquartile range of the Mg# (**Figures 3**, **4A**). This suggests that different batches of magma undergo independent ascent and cooling histories, and the extent of fractionation is more or less random. This idea is supported by the wide range in La_n/Sm_n and Sm_n/Yb_n, which precludes homogenization of distinct magma batches in a long-lived magma body (**Figures 3**, **4B,C**). Previous estimates of the depth of crystallization indicate that magmas supplying the eastern volcanoes undergo crystallization in the middle and deep crust, and only a few cool and crystallize in the shallow crust (Geist et al., 1998).

On the basis of their age (∼1 Ma), proximity, and the occurrence of rhyolites, trachytes, and dacites, we separate Santiago, Pinzón, and Rábida from the eastern province and define a new "intermediate" province. These three volcanoes have very large interquartile ranges of Mg# (**Figures 3**, **4A**), as one would expect from the existence of strongly evolved lavas. In many respects, their petrologic suites resemble that of Alcedo volcano, although the intermediate volcanoes are morphologically quite different from Alcedo. These observations indicate that although at 1 Ma the intermediate volcanoes erupted in a tectonic environment different than that of the present-day western Galápagos, and that the magma flux was likely different at the time, these volcanoes each had dying mush columns, from which evolved magmas were produced by extensive fractional crystallization (e.g., Geist et al., 2014).

Depth of Melt Generation

The western volcanoes have systematically higher Sm_n/Yb_n ratios than the eastern volcanoes, and the intermediate volcanoes have transitional values of Sm_n/Yb_n. This suggests a greater role for garnet beneath the western volcanoes, an idea that has been suggested previously in studies of both individual volcanoes (Geist et al., 1986, 2005; Harpp et al., 2014) and regional studies (White et al., 1993; Gibson and Geist, 2010). In turn, the garnet signature is equated to deeper melting, both due to hotter upwelling mantle and a thicker lithospheric lid (Villagómez et al., 2007, 2011; Gibson and Geist, 2010).

The parameterization of Gibson and Geist (2010) permits the conversion of Sm_n/Yb_n (**Figures 3**, **4B**) into an estimation of the depth to the top of the melting column (D_{top}); the deeper the top of the melting column, the greater the influence of garnet and the higher the Sm_n/Yb_n. The greatest D_{top} is 58 km at Volcan Wolf, despite being the western volcano closest to the GSC. The estimated top of the melting column then decreases in depth to the south and east, reaching 56–57 km at Alcedo and Sierra Negra volcanoes. The intermediate volcanoes do not show a southward gradient in D_{top}, but they have transitional values ranging from 51 km at Santiago to 57 km at Rábida. In contrast, the D_{top} estimates for the eastern islands are all shallower than the western volcanoes, from 51 km at San Cristóbal to 53 km at Santa Cruz.

The primary conclusion from the D_{top} comparison is that the melting regime has changed systematically over the past 3 million years in the Galápagos. Between 1 and 3 million years ago, the volcanoes that were most active were derived from relatively shallow melting, owing to a thinner lithospheric lid. The average depth of melting then deepened by 1.0–0.7 Ma, when the Intermediate volcanoes were most active, and it is deepest with the currently active volcanoes in the western Galápagos (**Figure 4B**).

Extent of Melting

Average $\Delta La_n/Sm_n$, which we use as a measure of' the average extent of melting, does not correlate well with any other parameter considered in this paper, with a single exception. These parameters include island age, the estimated top of the melting column (D_{top}), and the morphology of the volcano. The exceptions are the southern volcanoes of the eastern province, Floreana, Española, and San Cristóbal, which all have substantially higher $\Delta La_n/Sm_n$ than the other volcanoes (**Figure 5**), indicating that they are constructed of magmas generated from lower extents of melting that is observed in the rest of the Galápagos. These volcanoes are all south of the central axis of the archipelago, furthest from the GSC. Notably, the southern volcanoes of the currently active western Galápagos (Cerro Azul and Sierra Negra) do not share this characteristic.

The variability in La_n/Sm_n (and $\Delta La_n/Sm_n$), as measured by the interquartile range (and standard deviation), differs between the eastern and western volcanoes. The western volcanoes vary relatively little (except Cerro Azul; **Figures 3**, **4C**, **5**), in contrast to the eastern volcanoes, which exhibit considerable ranges in La_n/Sm_n and $\Delta La_n/Sm_n$. As with most other parameters, the intermediate volcanoes are transitional in La_n/Sm_n. We attribute the widely different variations in extent of melting to be due to two factors. First, the variable compositions in the east may be due to melts being extracted from different parts of the melt column; basalts with high La_n/Sm_n originate from the deeper segments, where upwelling mantle is just beginning to melt, and basalts with lower La_n/Sm_n come from the more extensively melted upper parts of the melt column. Second, the compositionally diverse melts from the eastern volcanoes must never have been homogenized in a long-lived magmatic plumbing system.

To interpret melt generation systematics in the Galápagos, we must also consider the homogeneity of basalts from the western volcanoes. Do these melts all originate from the same part of a variably melted zone in the mantle, or are heterogeneous melts from different parts of the column homogenized in the lithospheric plumbing system prior to eruption? Melt inclusion data from Fernanandina suggest that heterogeneous melts are hybridized, because although the bulk-rocks have little compositional diversity, olivine-hosted melt inclusions exhibit a range of major element (Hedfield and Geist, 2003), trace element (Koleszar et al., 2009), and isotopic heterogeneity (Peterson et al., 2014).

Cerro Azul is the exceptional western volcano, with relatively large variation in La_n/Sm_n (**Figures 3**, **4C**, **5**). This observation is consistent with the relatively large variation in Mg# (**Figures 3**, **4A**) at Cerro Azul and the geophysical observation that it lacks a shallow subcaldera magma reservoir (e.g., Amelung et al., 2000; Geist et al., 2014). Because it is still in a juvenile, developing phase, and because it lacks a well-connected crustal-scale mush column, heterogeneity is preserved as the melts ascend (e.g., Geist et al., 2014).

A Non-evolutionary Model for Galápagos Volcanism

On the basis of major element systematics and petrologic observations exclusively from the western Galápagos shields (see Geist et al., 2014, and references therein), Geist et al. (2014) constructed a three-stage evolutionary model for Galápagos volcanoes:

1. The Juvenile Transient Phase: As volcanoes begin to grow at the leading edge of the hotspot, batches of hot, relatively primitive magma undergo cooling and crystallization throughout the crust. On average, magma reservoirs are relatively small, hot, isolated, and deep, as the volcano's plumbing system begins to be established by a waxing magma supply. Geist et al. (2014) place Cerro Azul (Naumann and Geist, 2000) and Ecuador Volcanoes (Geist et al., 2002) in this stage (in this work, it is clear however that Ecuador belongs in the Mature Steady State Phase, below, owing to its lack of petrologic and geochemical variability). The crust thickens from ~8 to ~15 km in this phase (Feighner and Richards, 1994).
2. The Mature Steady State Phase: As magma supply increases, individual reservoirs coalesce into a several kilometer-thick mush zone, permitting a compositional and thermal steady state to be established. Within the plumbing system, magmas experience partial crystallization, maintaining a sill 1–3 km beneath the caldera surface with a temperature of ~1,150°C. Consequently, erupted lavas are moderately evolved and relatively homogeneous compared to other constructional phases. Fernandina (Allan and Simkin, 2000), Wolf (Geist et al., 2005), and Darwin Volcanoes (Naumann, pers. comm., 2017) are currently in this stage, according to Geist et al. (2014). This stage thickens the crust to ~18 km (Feighner and Richards, 1994).
3. The Dying Cooling Phase: Once carried away from the plume center, a volcano's magma supply wanes, causing the reservoir to cool below 1050°C, crystallize further, and erupt cooler lavas. Variable but significant amounts of crystallization result in a wide range of erupted compositions, extending in some cases (i.e., Alcedo) all the way to rhyolite (Geist et al., 1995). Geist et al. (2014) put Alcedo and Sierra Negra in this waning stage.

The Geist et al. (2014) evolutionary model for the Galápagos is primarily a function of the available magma flux, with the extent of shallow fractionation increasing with the age of the volcano. This evolutionary model bears broad resemblance to mechanisms proposed to explain geochemical and petrologic variations in the Hawaiian Islands. Lavas erupted during the shield-building phases are tholeiitic and exhibit little compositional variation, whereas post-shield lavas are the result of significant differentiation as the magma supply wanes (Macdonald et al., 1983; Clague and Dalrymple, 1987, 1988; Walker, 1990; Stolper et al., 2004). Increased extents of differentiation during the youngest waning phase of volcanism is a common theme at other ocean island volcanoes as well, including La Palma in the Canary Islands (Klügel et al., 2017).

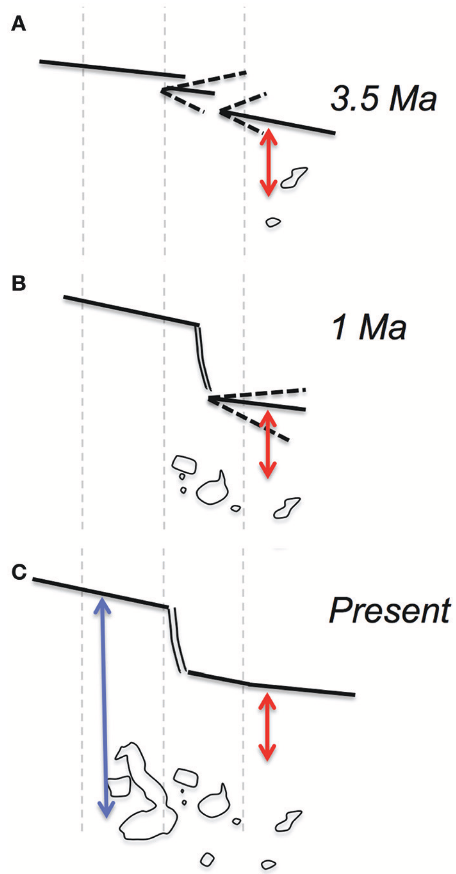

FIGURE 6 | Evolution of the Galápagos hotspot-GSC system since 3.5 Ma, after Mittelstaedt et al. (2012). Note that the coastlines of the volcanoes are drawn as they appear today and do not reflect older shapes of the islands. **(A)** At the time of the formation of San Cristóbal and Espanola, the distance between the plume and the GSC was <100 km, indicated by the red arrow, which is included for each of the time intervals for reference. **(B)** By 1 Ma, the GSC had drifted more than 100 km north, away from the Galápagos plume, but the eastern segment jumped south, creating the incipient transform at 90.5° W. Thus, at the time that Santiago, Rábida, and Pinzón were directly over the plume, the eastern segment of the GSC was close, but the western segment was >200 km away. **(C)** The blue arrow indicates the current distance from the seismically imaged plume and the GSC.

We hypothesize that the eastern volcanoes have undergone little evolution since they emerged on pre-existing oceanic lithosphere above the hotspot; they have always erupted more primitive and compositionally heterogeneous basalts from tectonically controlled edifices. This implies a discrete shift in the fundamental set of conditions responsible for volcano formation between 1 Ma and the present (**Figure 6**). The most obvious differences were that the GSC was closer to the plume at 3 Ma than it is today, and the long transform fault at 90.5°W was opening due to northward motion of the GSC relative to the plume and 2 discrete southward jumps of the GSC (Wilson and Hey, 1995; Mittelstaedt et al., 2012).

The proximity of the GSC to the plume from 1 to 3 Ma is consistent with the strong tectonic controls during constructional volcanism in the eastern Galápagos. In fact, the elongation of the volcanoes and the volcanic lineaments and fault orientations in the eastern Galápagos are in many ways comparable to similar structures in the present near-ridge Northern Galápagos Province (Harpp et al., 2014). For example, the structure of San Cristóbal is subparallel to Genovesa Ridge (the submarine fissure system that extends to the east of the island), which has been attributed to the stresses around the outside corner of a ridge-transform intersection (Harpp and Geist, 2002; Harpp et al., 2003). The E-W to WNW structures that control the morphologies of Santiago, Santa Cruz, Santa Fe, and Española islands are comparable to ridge-parallel fault patterns in the Northern Galápagos Province (Mittelstaedt et al., 2012).

Our interpretation is that the eastern volcanoes result from low magma fluxes relative to their western counterparts. Lower magma productivity accounts for the absence of a crustal mush column, which buffers the compositions of the magmas and produces a compositionally homogeneous product in the western volcanoes. It also accounts for the absence of hidden calderas in the eastern archipelago. The lower magma productivity, however, is at odds with the interpretation that the top of the melting column was shallower beneath the eastern and intermediate volcanoes from 1 to 3 Ma than it is beneath the western volcanoes (**Figure 4B**). This explanation is paradoxical; most models of near-ridge volcanism predict greater productivity with a shallower lithospheric lid (e.g., Regelous et al., 2003). One possible resolution is that the Galápagos plume has become more robust over the past million years, developing a greater magma flux despite the thicker lithospheric lid. This is a challenging hypothesis to test, although it may be reasonable given both long- and short-term evidence for large variations in the flux of the Hawaiian plume (e.g., Wessel, 2015). Another possibility is that the proximal GSC siphons magma from the hotspot province, for example through melt-rich channels between the plume and ridge (Mittal and Richards, 2017).

CONCLUSIONS

The Galápagos Archipelago underwent a distinct change in volcano morphology and magma compositions ∼1 Ma, which resulted from an evolving tectonic regime, emplacement onto thicker lithosphere, and waxing magmatic flux. The eastern volcanoes were emplaced in a near-ridge environment with a lower magma supply rate. The eastern volcanoes never had large calderas like the present-day western islands and had relatively magma-starved, ephemeral magmatic plumbing systems, leading to the eruption of more primitive magmas with large differences in incompatible trace-element compositions. Regional-scale tectonic stresses caused magma to be directed along strongly oriented fissures, and the volcanoes underwent faulting.

At about 1 Ma, when the intermediate islands of Pinzón, Rábida, and Santiago were forming over the hotspot, the tectonic setting was changing. The principal difference is that the separation between the plume and the GSC increased, owing to the northward motion of the GSC (Wilson and Hey, 1995; Mittelstaedt et al., 2012). Notably, the distance between the ridge and the still-active eastern volcanoes did not increase appreciably (**Figure 6**), owing to southward jumps of the eastern GSC and the formation of the large transform at 90.5°W. The lithosphere is thicker beneath the central islands, and the erupted magmas had largely been homogenized in the magmatic plumbing systems. Santiago, which was closer to the ridge during its peak activity, had strong tectonic controls on its morphology. Bodies of mush were of consequential size, so when the volcanoes were carried off the hotspot and the mush columns cooled and crystallized, and dacites, trachytes, and rhyolites formed.

For the past 0.5 Ma, the western Galápagos volcanoes have been forming farther from the GSC than any other active volcano in the province for at least the past 5 million years. Thus, they are being built on relatively thick lithosphere, and a greater fraction of the melt being created by the Galápagos plume is being fed to the Galápagos Archipelago and less to the GSC. Consequently, after an initial phase of volcano growth, the magmatic plumbing systems are dominated by a crustal scale mush column, which homogenizes and thermally and chemically buffers the magma composition. The robust magma supply and relatively small influence of regional tectonic stresses lead to nearly radially symmetric volcanoes topped by large calderas, owing to the presence of a well-developed shallow magma chamber. As these volcanoes are carried off the hotspot, the mush column cools and solidifies, producing highly evolved melts.

This view of the development of Galápagos volcanoes is very different than that at Hawaii, where the prevailing theory is that there is a consistent evolutionary trend. This results in similar stratigraphy from island to island, which in turn is dictated by common changes in eruption style and magma compositions. Because of the constantly changing tectonic environment, Galápagos volcanoes have followed disparate lineages from different precursors, analogous to phylogenic lineages from separate nodes. The eastern volcanoes form one evolutionary lineage, driven by proximity of the GSC and relatively low magmatic supply rates. The intermediate volcanoes formed at a time when the GSC was transitioning from a proximal to a distal setting relative to the plume. The currently most active western shield volcanoes are forming farthest from the GSC and have a magma supply that has been unprecedented in the past 5 million years.

AUTHOR CONTRIBUTIONS

KH conceived of the idea of this paper, designed some of the analysis, performed the calculations, and organized its structure; DG wrote several of the sections, designed some of the analysis, and contributed to the discussion section.

ACKNOWLEDGMENTS

KH would like to acknowledge support from National Science Foundation grant EAR 1347731. DG's effort is based upon work while serving at the National Science Foundation and funded by NSF grant EAR-1145271. Special thanks to important contributions from University of Idaho graduate students Darin Schwartz and Emily Wilson, and Colgate undergraduates Rita Van Kirk, Maggie McGuire, Kevin Varga, Jake Mahr, Regina Pimentel, Hannah Bercovici. We also thank Marco Córdova Aguilar and Marco Almeida, volcanology students from the Instituto Geofisico de Quito for their efforts in the field. We extend our gratitude for the generous assistance and permission from the Galápagos National Park and the Charles Darwin Research Station. Captain Lenin Cruz and the R/V Pirata provided invaluable support in the field. We would like to thank the reviewers, Tim Druitt, Connie Class, Andreas Klugel, and Alessandro Tibaldi, for their thoughtful comments on an earlier draft, and Ricardo Ramalho for inviting us to contribute to this research topic and his editorial prowess.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.