Missing history (16–71 Ma) of the Galápagos hotspot: Implications for the tectonic and biological evolution of the Americas

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ABSTRACT

We present the results of volcanological, geochemical, and geochronological studies of volcanic rocks from Malpelo Island on the Nazca plate (15.8–17.3 Ma) belonging to the Galápagos hotspot tracks, and igneous complexes (20.8–71.3 Ma) along the Pacific margin of Costa Rica and Panama. The igneous complexes consist of accreted portions of ocean island and seamount volcanoes and aseismic ridges, representing the missing (primarily subducted) history of the Galápagos hotspot. The age and geochemical data directly link the Galápagos hotspot tracks on the Pacific Ocean floor to the Caribbean large igneous province (ca. 72–95 Ma), confirming a Pacific origin for the Caribbean oceanic plateau from the Galápagos hotspot. We propose that emplacement of this oceanic plateau between the Americas and interaction of the Galápagos hotspot tracks with the Central American Arc played a fundamental role in the formation of land bridges between the Americas in Late Cretaceous–Paleocene and Pliocene-Holocene time. The land bridges allowed the exchange of terrestrial faunas (e.g., dinosaurs, mastodons, saber-tooth cats, and ground sloths) between the Americas and served as barriers for the exchange of marine organisms between the central Pacific Ocean and the Caribbean Sea and the central Atlantic Ocean.

Keywords: Galápagos hotspot, Caribbean large igneous province, Caribbean plate, oceanic plateau, Central American Arc, inter-American land bridges, biotic exchange, evolution, $^{40}Ar/^{39}Ar$ geochronology, trace element, Sr-Nd-Pb isotope geochemistry.

INTRODUCTION

The Galápagos hotspot has formed tracks on the Cocos and Nazca plates extending from the Galápagos Islands (currently located above the hotspot) to the Central American and Ecuadorian deep-sea trenches (Fig. 1). The Galápagos hotspot track off the coast of Costa Rica is 13.0–14.5 Ma and consists of the tholeiitic Cocos Ridge and discrete alkalic seamounts on its northwest margin (Werner et al., 1999; Hoernle et al., 2000). The Coiba Ridge, most likely an extension of the Cocos Ridge offset to the south along the Panama Fracture Zone (Fig. 1), has a geochemical composition consistent with derivation from the Galápagos hotspot (Hauff et al., 2000a). The Malpelo Ridge (Fig. 1) was separated from the Carnegie Ridge in the Miocene by now-extinct seafloor spreading (Lonsdale and Klitgord, 1978). The earlier record of the Galápagos hotspot has presumably been subducted beneath Central and South America. Models for the origin of igneous complexes along the Pacific coast of Central America range from uplift of in situ Caribbean basement to subduction-zone volcanism to accretion of normal oceanic crust or Galápagos hotspot tracks (summary in Hauff et al., 1997, 2000a).

The Caribbean large igneous province represents a period of extreme volcanism and intrusive activity between 72 and 95 Ma (Fig. 2B) that formed an oceanic plateau that subsequently became the Caribbean plate. Two fundamentally different origins have been proposed for this large igneous province: (1) in situ formation between the Americas (e.g., Ball et al., 1969; Donnelly, 1985), and (2) formation in the eastern Pacific (e.g., Burke et al., 1978; Pindell and Dewey, 1982), most likely from the Galápagos hotspot (e.g., Duncan and Hargraves, 1984; Sinton et al., 1997; Hauff et al., 1997) (summary in Meschede and Frisch, 1998). The occurrence of radiolarites in the Greater Antilles with Pacific faunal affinities and Jurassic ages older than the presumed separation of the Americas necessitates a Pacific origin for the Caribbean plate (e.g.,

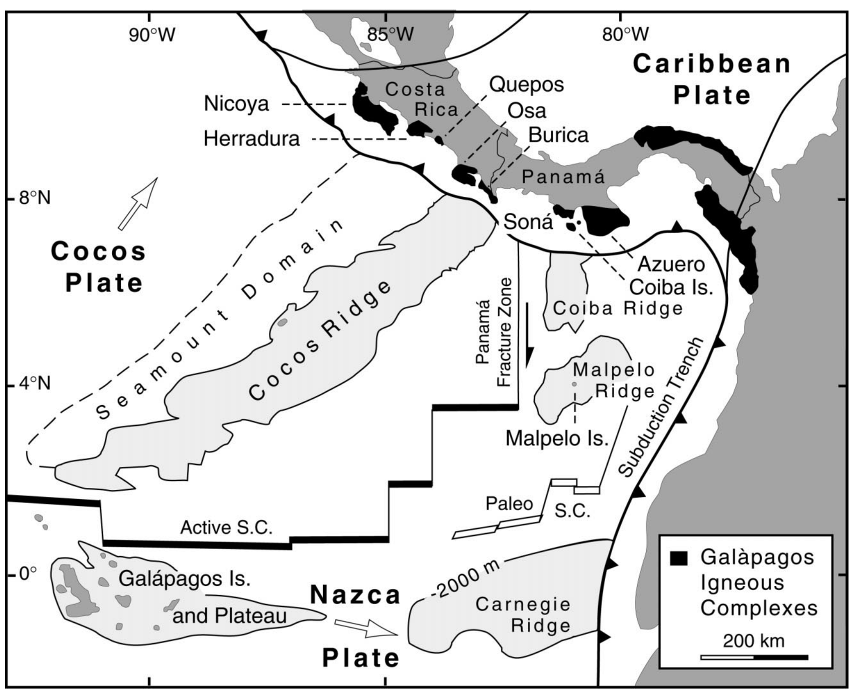

Figure 1. Galápagos Islands and hotspot tracks (Cocos, Coiba, Malpelo, and Carnegie Ridges), igneous complexes in Central America with Galápagos geochemical affinities, and western portion of Caribbean plate. Is. is Island, S.C. is spreading center.

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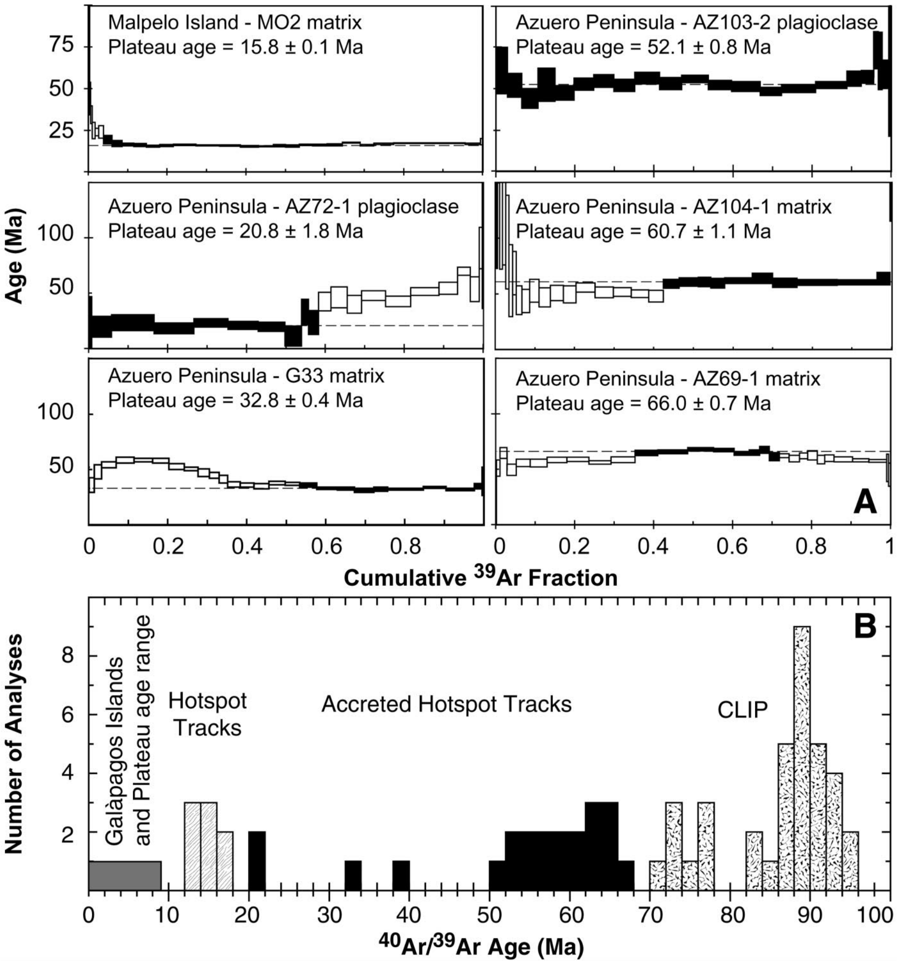

Figure 2. A: Representative ^{39}Ar step-heating diagrams filling in missing history of Galápagos hotspot. B: Summary of ^{40}Ar/^{39}Ar age data from Galápagos hotspot tracks, accreted Galápagos tracks in Central America, and Caribbean large igneous province (CLIP). Data are from Appendix 1 (see text footnote 1) and Kerr et al. (1997), Sinton et al. (1997, 1998), Werner et al. (1999), Hauff et al. (2000a, 2000b), White et al. (1993), and Christie et al. (1992).

Montgomery et al., 1994). A major argument against derivation of the Caribbean igneous province from the Galápagos hotspot has been the lack of evidence for 57 m.y. of Galápagos volcanism, between the dated hotspot tracks (15 Ma) on the Pacific seafloor and the Caribbean igneous event (72–95 Ma). Our results from Malpelo Island and accreted igneous complexes in Central America show that the Galápagos hotspot was active from 16 to 71 Ma, confirming that the Caribbean large igneous province formed from the Galápagos hotspot and that the Caribbean plate originated in the Pacific.

The Galápagos Islands are renowned for the role their unique endemic fauna played in the development of the theory of evolution (Darwin, 1859). The reconstruction of the missing history of the Galápagos allows us to present a model for the tectonic evolution of the East Pacific and Caribbean region, demonstrating that the long-lived activity of the Galápagos hotspot was ultimately responsible for the formation of land bridges that connected the Americas and separated the central Pacific Ocean from the Caribbean and the central Atlantic Ocean in Late Cretaceous–Paleocene and Pliocene-Holocene time. Therefore the Galápagos hotspot made a far greater contribution to evolutionary biology than previously recognized, not only facilitating the exchange of terrestrial fauna between the Americas, but also inhibiting the exchange of marine faunas between the Earth's largest oceans. The closing of the marine gateway between the Americas also caused major changes in the pattern of ocean circulation, affecting the global climate.

RESULTS

Accreted volcanic sequences in Central America (Fig. 1) range from highly vesicular, oxidized lava flows and agglutinates deposited under subaerial conditions to pillow lavas deposited under submarine conditions. Volcaniclastic sequences containing red-oxidized lava and shallow-water carbonate are common, and may reflect clastic aprons associated with island volcanoes. Some of the subaerial volcanic sequences are capped by shallow-water carbonates, suggesting drowning of former ocean-island volcanoes before they were accreted.

Volcanic rocks from Malpelo Island yielded ^{40}Ar/^{39}Ar ages of 15.8 ± 0.1 Ma, 16.7 ± 0.5 Ma, and 17.3 ± 0.3 Ma (Fig. 2; Appendix 1[1]), providing a minimum age for the former Malpelo–Carnegie Ridge hotspot track. The ^{40}Ar/^{39}Ar ages from lava flows and pillow basalts from Panamá range from 21 to 71 Ma (southern Azuero Peninsula: 20.8 ± 1.8, 21.2 ± 1.0, 32.8 ± 0.5, 51.9 ± 1.3, 52.1 ± 0.8, 52.6 ± 0.6, 54.4 ± 1.5, 56.0 ± 1.7, 58.6 ± 0.3, 60.7 ± 1.1, 61.7 ± 1.2, 63.2 ± 0.6, 66.0 ± 0.7 Ma; Coiba Island: 38.2 ± 2.4 Ma; Sona Peninsula: 71.3 ± 2.1 Ma). Samples from the Osa and Burica Peninsulas of Costa Rica were dated as 54.5 ± 1.5 and 64.2 ± 1.1 Ma, respectively, similar to a published ^{40}Ar/^{39}Ar age of 62.1 Ma from Osa (Hauff et al., 2000a). A basalt from the Quepos accreted ocean-island complex in Costa Rica produced an ^{40}Ar/^{39}Ar age of 65.0 ± 0.4 Ma, slightly older than previously reported ^{40}Ar/^{39}Ar ages of 60.1 Ma (Sinton et al., 1997) and 59.4 Ma (Hauff et al., 2000a). The ^{40}Ar/^{39}Ar ages ranging from 83 to 95 Ma have been published for rocks from the Nicoya and Herradura igneous complexes in northwestern Costa Rica and are interpreted to be uplifted portions of the Caribbean large igneous province (Sinton et al., 1997; Hauff et al., 2000a, 2000b).

The tholeiitic and alkalic basalts from the 21–71 Ma Central American igneous complexes have higher incompatible element concentrations and Pb isotope ratios, but lower Nd isotope ratios than Pacific oceanic crust, and have distinct trace element characteristics from subduction-zone volcanic rocks, e.g., peaks for Nb and Ta instead of troughs, and troughs for Pb instead of peaks on multielement diagrams (Fig. 3). The major and trace element and Nd-Pb isotopic compositions of the samples (Appendix 2; see footnote 1), however, are strikingly similar to those of volcanic rocks from the Galápagos Islands and hotspot tracks and the Caribbean large igneous province (Fig. 3), consistent with their origin from the Galápagos hotspot.

DISCUSSION AND CONCLUSIONS

The ^{40}Ar/^{39}Ar ages from Malpelo Island extend the age of the preserved Galápagos hotspot tracks to 17.3 ± 0.3 Ma. The field, geochemical, and geochronological investigations of the igneous complexes along the Pacific

[1]GSA Data Repository item 2002092, Appendices 1 and 2, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2002.htm.

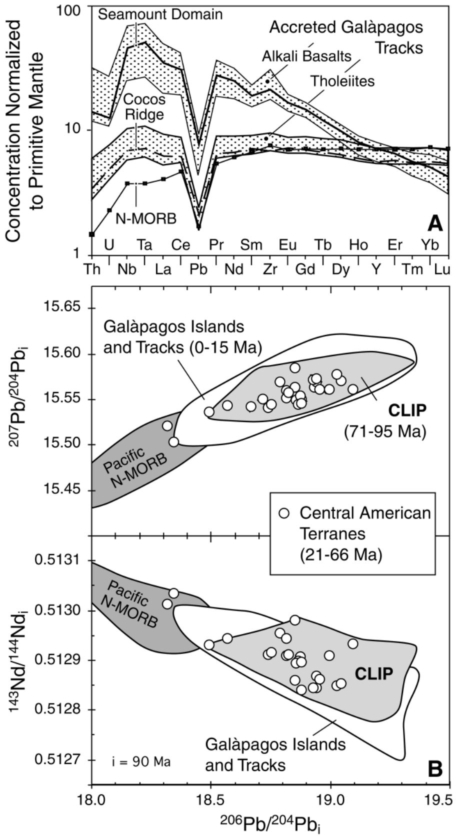

Figure 3. A: Incompatible element concentrations normalized to primitive mantle for tholeiites and alkali basalts from Central American terranes (16–71 Ma) are higher than normal mid-ocean-ridge basalt (N-MORB), but are similar to basalts from Galápagos hotspot track (tholeiite from Cocos Ridge and alkali basalt from seamount domain; Hoernle et al., 2000). B: Isotope ratios for Central American accreted terranes differ from Pacific Ocean crust (Pacific N-MORB, including Cocos-Nazca spreading center), but are within range of Galápagos Islands (excluding Floreana) and hotspot tracks and Caribbean large igneous province (CLIP) (White et al., 1993; Hauff et al., 1997, 2000a, 2000b; Hoernle et al., 2000). Data have been corrected for radioactive decay to 90 Ma (see Hauff et al., 2000b).

coast of Central America show that they represent accreted pieces of the subducted Galápagos hotspot tracks (21–66 Ma). The 71.3 ± 2.1 Ma pillow sequence on the Sona Peninsula is interpreted to belong to the Caribbean igneous province (ca. 72–95 Ma). These new data directly link the Galápagos tracks on the Cocos and Nazca plates to the Caribbean large igneous province, confirming that the province formed in the Pacific above and from the Galápagos hotspot and then drifted northeastward to arrive at its present location between the Americas.

The published $^{40}Ar/^{39}Ar$ age data indicate that at its peak (89 Ma, Fig. 2B) Caribbean igneous activity occurred across the entire oceanic plateau (Sinton et al., 1998). Igneous activity younger than 83 Ma has only been found on the Beata Ridge (central Caribbean) and along the western margin of the igneous province, consistent with eastward movement of the province and lower magma production during the latter stage of the igneous event. The transition from Caribbean to (accreted) hotspot-track igneous activity coincides with the passage of the province margin over the Galápagos hotspot (66–71 Ma). The dense cluster of older ages (52–66 Ma; n = 16) of the accreted complexes, as compared to the sparse younger ages (21–51 Ma; n = 4) (Fig. 2B), reflects a combination of factors, including sampling bias, because most of the younger accreted terranes are probably offshore (the four youngest ages are the closest to the former trench off the coast of Panama), and a higher rate of accretion between 52 and 66 Ma. Greater accretion during the earlier history of the hotspot probably reflects higher magma production rates, and subduction of younger (and thus hotter and more buoyant, as well as less eroded and thus higher) volcanic structures, because the hotspot was closer to the trench. Some gaps in the Galápagos hotspot record may also reflect subduction erosion. Our results, however, indicate that accretion has been the dominant process over the past 70 m.y., contributing to the growth of the Central American land bridge.

We briefly summarize the tectonic evolution of the Americas in the Mesozoic and Cenozoic and present a tectonic model for the evolution of the eastern Pacific and Caribbean that illustrates the essential role that the Galápagos hotspot played in forming two land bridges between the Americas. In the Jurassic, North America separated from Gondwana (southern supercontinent) and drifted to the northwest. Africa and South America began drifting apart ca. 130 Ma, leaving South America as a continental island similar to Australia at the present. Biotic exchange (ancient immigrants) between North and South America provides evidence that the Greater Antilles formed a complete land barrier between the Americas in Late Cretaceous and possibly early Paleocene time (e.g., Hill, 1898; Simpson, 1965; Rage, 1988; Alvarado, 1994). Dinosaurs (hadrosaurids, ceratopsians), mammals (condylarths), and possibly lizards (teiids) dispersed southward, whereas other dinosaur species (tiranosaurids), snakes (aniliids, boines), and perhaps iguanid lizards and bothremydid turtles dispersed northward (e.g., Bonaparte, 1984; Alvarado, 1994). During most of the Tertiary, the Americas were again separated. Differentiation of planktonic species between the Caribbean and Pacific and the geochemistry of marine sediments indicate closure of the seaway between the Americas in the early Pliocene (Keigwin, 1978), resulting in a major reorganization of ocean circulation patterns

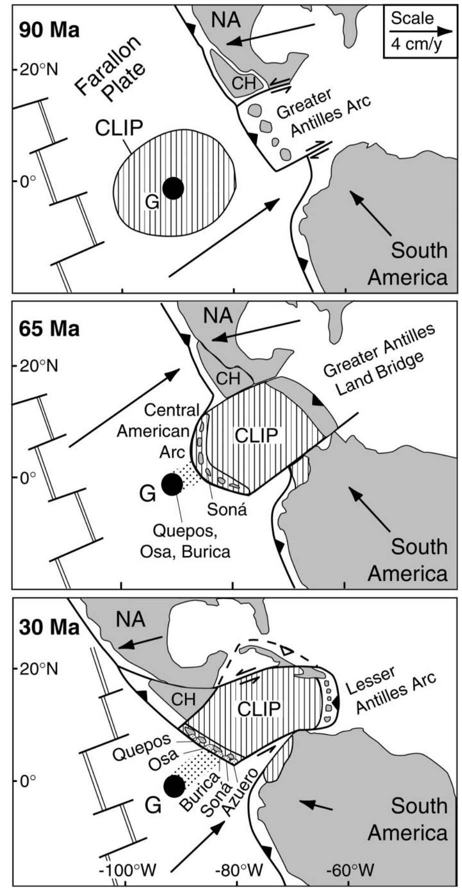

Figure 4. Tectonic model for evolution of eastern Pacific and Caribbean over past 90 m.y. (based on Burke, 1988; Duncan and Hargraves, 1984; Pindell and Barrett, 1990) illustrating fundamental role that products of Galápagos hotspot (i.e., emplacement of Caribbean large igneous province [CLIP] between Americas and interaction of Galápagos hotspot track with Central American Arc) played in formation of Late Cretaceous–Paleocene and Pliocene-Holocene land bridges and marine barriers between Americas. NA is North America, G is Galápagos hotspot, CH is Chortis block.

and climate change (glacial-interglacial oscillations) starting at 4.6 Ma (Haug and Tiedemann, 1998). Significant biotic interchange between North and South America, including, e.g., mastodons, saber-tooth cats, tapirs, ground sloths, and armadillos, however, did not begin until 3.1–3.7 Ma (e.g., Webb, 1976; Alvarado, 1994).

The role of the Galápagos hotspot in the plate tectonic evolution of the eastern Pacific and Caribbean is illustrated in Figure 4. By ca. 85 Ma, the Caribbean oceanic plateau had formed above the Galápagos hotspot and began drifting northeastward toward the Greater Antilles Arc. The eastern edge of the thick (to 20 km) and young (thus hot and buoyant) oceanic plateau choked east-dipping subduction beneath the Greater Antilles Trench ca. 70–75 Ma, causing uplift of the arc and the formation of a land bridge between the Americas in the latest Cretaceous. In compensation for the clogged east-dipping subduction, west-dipping subduction developed along the eastern margin of the Greater Antilles, allowing for the dislocation of the land bridge in the early Paleocene and the insertion of the Caribbean large igneous province between the Americas.

East-dipping subduction beneath the western edge of the Caribbean large igneous province led to formation of the Central American Arc, possibly also triggered by the polarity reversal in subduction at the Greater Antilles Arc. Because oceanic plateaus are substantially shallower than normal oceanic crust, the location of the Central American Arc on the initial products of the Galápagos hotspot was the first step in the formation of the Central American land bridge. Although most of the Galápagos hotspot tracks formed between 20 and 70 Ma were subducted, larger seamount complexes, drowned ocean islands, and portions of aseismic ridges were accreted to the western edge of the Central American Arc, serving to fill the gaps between individual arc volcanoes and between the arc and the Americas. A shift in the subduction of the Galápagos hotspot track along the Panama Fracture Zone (Fig. 1), from western Panama (Coiba Ridge track) to southern Costa Rica (Cocos Ridge track), resulted in uplift of southern Costa Rica beginning ca. 5 Ma (de Boer et al., 1995). This uplift may have been the final step in closing the marine gateway between the Americas at 4.6 Ma and in developing the Central American land bridge in the Pliocene.

The longevity and productivity of the Galápagos hotspot played a fundamental role in the development of land bridges between the Americas, permitting the exchange of biota between continents after the breakup of Pangea. These land bridges also served as marine barriers between the central Pacific Ocean and the proto–Caribbean Sea, Caribbean Sea, and Atlantic Ocean. The closure of the American gateway not only prevented the exchange of equatorial marine organisms between the oceans, but also triggered major changes in global oceanic circulation patterns and paleoclimate, which may have also contributed to extinctions.

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