70 m.y. history (139–69 Ma) for the Caribbean large igneous province

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ABSTRACT

It is commonly accepted that large igneous provinces are formed through catastrophic volcanic events occurring over vast areas within a few million years at the initiation of hotspots (mantle plumes). New $^{40}Ar/^{39}Ar$ ages (111–139 Ma) and geochemical results from the Nicoya Peninsula, Costa Rica, extend the age range of volcanism in the Caribbean large igneous province to 70 m.y. (69–139 Ma). Our results are not consistent with the formation of this vast igneous province through a single plume head at the initiation of a mantle plume such as the Galápagos. Instead we propose that multiple oceanic intraplate igneous structures, such as plateaus and hotspot tracks, were accumulated through the subduction process. The igneous structures could be remnants of the earlier history of the Galápagos hotspot, making it one of the oldest active hotspots on Earth. Alternatively they could have been derived from several spatially distinct mantle-melting events that sampled similar source material, e.g., oceanic lithosphere of similar age.

Keywords: Caribbean large igneous province, Galápagos hotspot, Nicoya Peninsula, Central American subduction, $^{40}Ar/^{39}Ar$ geochronology, geochemistry.

INTRODUCTION

Oceanic and continental flood-basalt provinces, termed large igneous provinces, represent the most voluminous igneous events on our planet (e.g., Mahoney and Coffin, 1997). With the advent of $^{40}Ar/^{39}Ar$ incremental heating age determinations, the short-term nature of flood-basalt volcanism was established through the precision dating of continental flood basalts such as the Deccan Traps (67.4 ± 0.7 Ma; Duncan and Pyle, 1988) at the Cretaceous-Tertiary boundary. The formation of large igneous provinces has fundamental implications for the transfer of mass and energy from the interior of Earth to its surface and for the growth and breakup of continents. Large igneous provinces may also have contributed to global environmental change and mass biotic extinctions (Courtillot, 1999).

Many large igneous provinces are at the oldest end of hotspot tracks, which has led to the conclusion that they represent the initial stages of hotspot or plume activity. In order to explain the large volume, wide geographic distribution, and short time interval of large igneous province events, it has been proposed that plumes have large mushroom-shaped heads at their initiation (Griffiths and Campbell, 1990; Richards et al., 1989). Upon reaching the base of the lithosphere, these plume heads can flatten into disks with diameters up to 2500 km, generating widespread volcanism within short (several million year) time scales. Oceanic large igneous provinces form the largest igneous provinces on Earth (e.g., Ontong Java and Kerguelen Plateaus) and occur throughout the world's oceans (e.g., Mahoney and Coffin, 1997).

The Caribbean large igneous province is exceptional among oceanic plateaus, because a large proportion of its margins has been tectonically uplifted and is subaerially exposed. The province comprises thickened (up to 20 km) oceanic crust belonging to the Caribbean plate and flood-basalt sequences accreted to the northwest margin of South America. The province currently covers an area of ~2500 km (east to west) by ~1300 km (north to south) (Fig. 1). Published $^{40}Ar/^{39}Ar$ age determinations from throughout the province range from 95 to 69 Ma and place the main pulse of flood-basalt magmatism ca. 89 Ma (95–83 Ma), followed by a second pulse ca. 75 Ma (81–69 Ma) (Hauff et al., 2000a; Hoernle et al., 2002; Kerr et al., 1997; Révillon et al., 2000; Sinton et al., 1997, 1998).

Most studies have related the simultaneous occurrence of volcanism at 89 ± 6 Ma over a large part of the Caribbean plate and northwest South America to the arrival of a single plume head at the initiation of the Galápagos hotspot (Duncan and Hargraves, 1984; Hauff et al., 1997, 2000a, 2000b; Sinton et al., 1997, 1998). The 75 Ma magmatic phase has been attributed to volcanism above the Galápagos hotspot tail and/or to lithospheric thinning accompanied by upwelling and melting of residual plume-head material (Sinton et al., 1998; Révillon et al., 2000; Hoernle et al., 2002). Seismic reflection profiles of the Caribbean (Mauffret and Leroy, 1997) and geochemistry combined with age dating (Kerr et al., 2000; Lapierre et al., 2000), however, suggest that the large igneous province may consist of portions of multiple oceanic plateaus. The age and geochemical data presented in this paper provide further evidence that the plume-head model must be reconsidered in respect to the origin of this province.

GEOLOGIC BACKGROUND AND RESULTS

The samples of this study come from the Nicoya Peninsula (Costa Rica), located at the southwestern edge of the Chortis block (Hauff et al., 2000a) (Fig. 1). It has been proposed that the Nicoya Complex consists of oceanic terranes accreted through plate-boundary jumping (Schmidt-Effing, 1980), forming an accretionary complex in the forearc of the Chortis subduction zone. Exposed igneous rocks include tholeiitic pillow lavas, sheet flows, and gabbros and plagiogranites. Radiolarian cherts, associated with the igneous rocks, range in age from Santonian to Callovian (164–84 Ma; for summary see Hauff et al., 2000a). Because severe tectonism has de-

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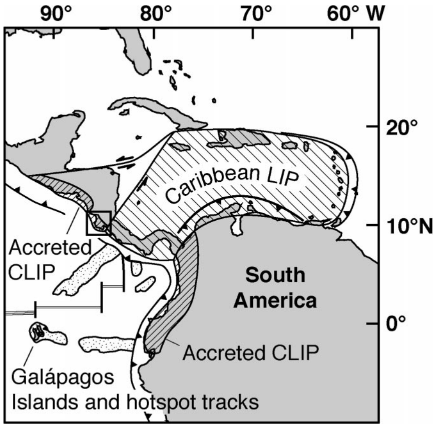

Figure 1. Map showing eastern Pacific including present location of Galápagos hotspot and Caribbean. Also shown are extent of Caribbean large igneous province (CLIP) and accreted terranes along Pacific margins of northwestern South America and Central America (Guatemala to northern Costa Rica). Box shows location of Nicoya Peninsula at southern tip of Chortis block.

stroyed most primary contacts, dating of the igneous rocks through biostratigraphic means is rarely possible. Published $^{40}Ar/^{39}Ar$ age determinations from tholeiitic lavas and intrusions yield an age range of 94.7–83.2 Ma (Hauff et al., 2000a; Sinton et al., 1997), thus far overlapping only the young end of the biostratigraphic age range.

We present $^{40}Ar/^{39}Ar$ age (Appendix DR1[1]; Fig. 2) and geochemical (Appendix DR2 [see footnote 1]; Figs. 3 and 4) data from fresh glass from pillow rinds and a fresh pillow core from the Nicoya Peninsula (Fig. 1). On the northern coast of Nicoya, three glass samples produced $^{40}Ar/^{39}Ar$ isochron ages of 139.1 ± 1.1 Ma (AN8), 137.6 ± 1.8 Ma (AN10), and 132.9 ± 1.5 Ma (AN3). A pillow sample from the northwestern coast of Nicoya was dated as 110.6 ± 0.9 Ma (BN22), whereas two glass samples from the central western coast produced ages of 119.4 ± 1.1 Ma (AN34) and 118.2 ± 1.8 Ma (AN40). Incremental heating plateau ages of 137 ± 2 Ma (AN10) and 118 ± 5 Ma (AN34) agree within error of the total fusion results from the same samples (Fig. 2).

The glasses and whole-rock samples are tholeiitic basalts with SiO_2 = 49–52 wt% and MgO = 4.8–7.9 wt%. Excellent correlations of Na_2O and K_2O with other major elements demonstrate that K and Na in the glasses have not been affected by alteration (Hauff et al., 1997). Incompatible elements form flat pat-

[1]GSA Data Repository item 2004114, Appendixes DR1 and DR2, is available online at www.geosociety.org/pubs/ft2004.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

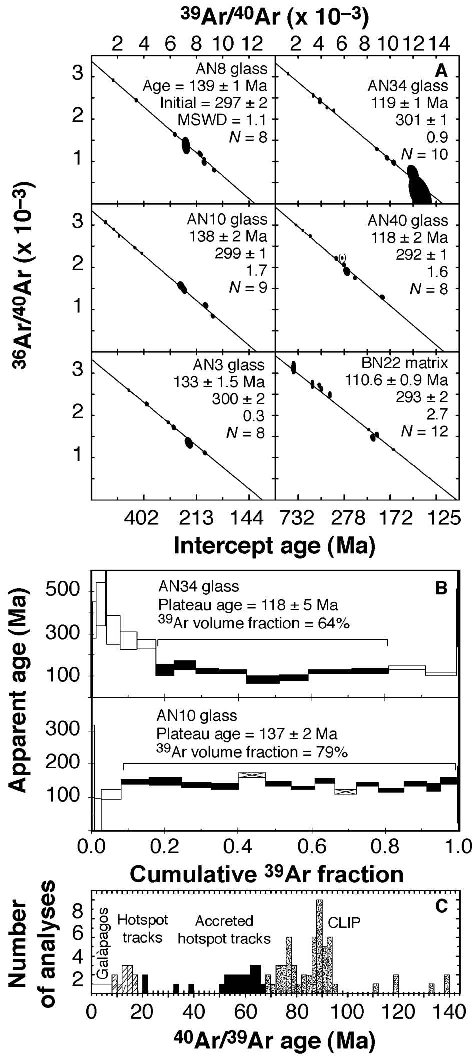

Figure 2. $^{40}Ar/^{39}Ar$ (A) isochron ages for five basalt glass samples and one matrix sample and (B) incremental step-heating plateau ages for two basalt glasses from Nicoya Peninsula range from 139 to 111 Ma, considerably extending age range of 95–83 Ma previously reported from Nicoya. C: Histogram of $^{40}Ar/^{39}Ar$ age data from Galápagos hotspot tracks, accreted paleo–hotspot tracks in Central America, and Caribbean large igneous province (CLIP), suggesting that Galápagos hotspot may have been active since at least 139 Ma and thus is one of longest-lived hotspots on Earth. Data and references for C are included in Appendix DR1 (see text footnote 1). MSWD—mean square of weighted deviates.

terns on multielement diagrams with relative depletions in Cs, Ba, Th, K, Pb, and Sr (Fig. 3). The Sr, Nd, and Pb isotope compositions of the basalts studied here are very similar to each other ($^{87}Sr/^{86}Sr$ = 0.70306–0.70319, $^{143}Nd/^{144}Nd$ = 0.513005–0.513022, $^{206}Pb/^{204}Pb$ = 19.06–19.24, $^{207}Pb/^{204}Pb$ = 15.55–15.58, and $^{208}Pb/^{204}Pb$ = 38.67–38.89) (Fig. 4).

DISCUSSION AND CONCLUSIONS

Three possibilities exist for the origin of these older (139–111 Ma) Nicoya pillow basalts: (1) subduction-zone volcanism along the western margin of the Chortis block; (2) mid-oceanic-ridge-basalt (MORB)–type oceanic crust forming the basement of the Caribbean large igneous province; and (3) earlier plume volcanism.

The petrology and geochemistry of the tholeiitic glasses can be used to distinguish between these possibilities. On multielement diagrams, subduction-zone basalts display peaks at fluid mobile elements such as Ba, K, Pb, and Sr and a trough at Nb and Ta. The Nicoya glass patterns, however, exhibit the opposite characteristics (Fig. 3). The Nicoya glasses also have higher Nb/U (41.9–46.5), Nd/Pb (22.7–25.3), Ce/Pb (28.7–32.5), $^{238}U/^{204}Pb$ (18.4–20.8), and $^{232}Th/^{204}Pb$ (56–62) ratios than subduction-zone basalts. The trace element characteristics clearly demonstrate that the Nicoya glasses are not derived through subduction-zone volcanism.

The chemical compositions of the glasses are also not consistent with their derivation from MORB-type oceanic crust. As reported by Hauff et al. (1997), the Na(8) (Na content at MgO = 8 wt%) of the Nicoya glasses is lower than that of Pacific MORB and extends to lower values than occur in global MORB not influenced by hotspots, consistent with higher temperatures and degrees of melting to form these melts compared to MORB. The incompatible element patterns of the Nicoya glasses cross those for normal MORB: Lu to Hf are lower and Ce to Cs are higher in the Nicoya glasses at a given MgO content (e.g., cf. sample AN34 with average normal [N]-MORB in Fig. 3). Because the Na(8) values suggest that degrees of melting were greater for the generation of the Nicoya glasses than for MORB, the higher Ce to Cs contents at similar MgO contents suggest derivation of the Nicoya glasses from a more enriched source than normal MORB. The higher Sr and Pb but lower Nd isotope ratios (Fig. 4) and the higher $^{238}U/^{204}Pb$ (18.4–20.8) and $^{232}Th/^{204}Pb$ (56–62) ratios in the Nicoya glasses compared to normal Pacific MORB also indicate derivation from a more enriched source than normal MORB.

Mesozoic Pacific MORB between 170 and 130 Ma in age displays depletion in highly incompatible elements (e.g., light rare earth elements, Nb, Ta, and Th), similar to modern Pacific MORB (Janney and Castillo, 1997). When compared at the same age, the Sr, Nd, and Pb isotopic compositions of the freshest samples are surprisingly uniform and similar to those of modern Pacific N-MORB (Fig. 4). Middle Cretaceous (115–100 Ma) western Pa-

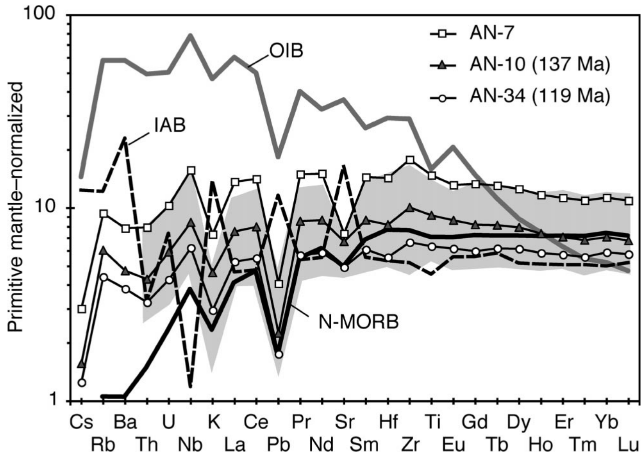

Figure 3. Primitive mantle–normalized multielement diagram of older (139–111 Ma) tholeiitic glasses from Nicoya Peninsula, demonstrating that their geochemical signatures are similar to those of 95–86 Ma Nicoya tholeiites (i.e., whole-rock data shown in gray field; Sinton et al., 1997; Hauff et al., 2000b). Cs, Rb, and Ba are not shown for whole rocks because they are most likely affected by alteration. Reference patterns for island-arc basalts (IAB), oceanic-island basalts (OIB), and normal mid-oceanic-ridge basalts (N-MORB) are also shown. Primitive mantle–normalized value for Cs in N-MORB plots below diagram at 0.26. Appendix DR2 (see text footnote 1) contains additional references.

cific MORB, in the vicinity of the Mesozoic Ontong Java and Manihiki Plateaus and Mid-Pacific Seamounts, however, has enriched highly incompatible element and initial Sr, Nd, and Pb isotope compositions. Janney and Castillo (1997) attributed the EM1-type isotopic affinity of the middle Cretaceous MORB to enrichment of the upper mantle through mixing with plumes and plume heads that produced the Ontong Java and Manihiki Plateau basalts ca. 122 Ma. The 139–117 Ma Nicoya glasses have more enriched incompatible element and radiogenic isotope compositions than 170–130 Ma Pacific MORB, but display less enrichment in highly incompatible elements than the 115–110 Ma west Pacific MORB and don't have EM1-type isotopic signatures. In summary, the major and trace element and isotope data of the Nicoya glasses are not consistent with derivation from ancient or modern N-MORB.

The isotopic compositions (corrected to a common age) of the Nicoya glasses are indistinguishable from (1) the majority of Caribbean large igneous province lavas formed between 95 and 69 Ma, (2) Galápagos Island basalts (4–0 Ma), and (3) the Galápagos hotspot track basalts on the Pacific seafloor and those accreted to the Pacific margin of Central America (66–2 Ma) (Fig. 4). The geochemistry of the Nicoya basalts is also similar to enriched MORB, commonly interpreted to reflect mixing between N-MORB and oceanic-island basalt sources in the form of plume-ridge interaction. Therefore, whether the older Nicoya samples were derived from enriched oceanic crust or older lavas of the province, both scenarios imply the involvement of mantle plumes or plume heads with Galápagos-like chemical composition.

As illustrated in the histogram in Figure 2C, the Caribbean large igneous province can be directly linked to the Galápagos hotspot through accreted terranes along the Pacific margin of southwestern Costa Rica and western Panama and the Cocos Ridge and Carnegie Ridge tracks on the Pacific seafloor (Hoernle et al., 2002). Paleomagnetic data from samples taken from the same or nearby localities from which the older Nicoya basalts were collected indicate derivation of the province from equatorial latitudes (Frisch et al., 1992), similar to the present location of the Galápagos hotspot. The presence of Jurassic radiolarians in the Greater Antilles with Pacific faunal affinities and ages older than the separation of the Americas provide additional evidence for a Pacific origin of the Caribbean plate (e.g., Montgomery et al., 1994). Taken together, the available petrologic, geochemical, geologic, paleomagnetic, and paleontological results are consistent with—although do not prove—an origin of the 83–139 Ma Nicoya igneous rocks from the Galápagos hotspot, which would make the Galápagos one of the longest-lived active plumes on Earth.

Our new age results from Nicoya basalts, however, indicate that the Caribbean province wasn't formed through a single plume head at 89 Ma, marking the initiation of the Galápagos hotspot as previously proposed. Accretion of fragments from several oceanic plateaus possibly formed by a pulsing Galápagos hotspot (Mauffret and Leroy, 1997), however, could explain the older (111–139 Ma) Nicoya magmatism, implying that multiple plume heads may be formed during the early history of some hotspots. Alternatively, the older Nicoya lavas may have been produced by several distinct hotspots derived from a common source reservoir or similar source material, e.g., recycled oceanic lithosphere with a crudely similar age (Hauff et al., 2000b).

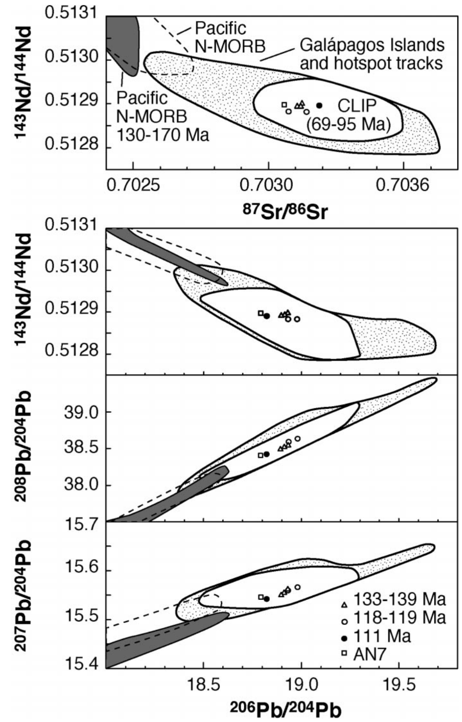

Figure 4. Sr, Nd, and Pb isotope ratios at 90 Ma for 139–111 Ma Nicoya basalts differ from present-day and 170–130 Ma Pacific ocean crust (normal mid-oceanic-ridge basalts [N-MORB]), but are within range of Caribbean large igneous province (CLIP, 95–69 Ma) and Galápagos Island and hotspot-track lavas (66–0 Ma). Isotope ratios at 90 Ma were calculated by assuming that Nicoya basalts have similar parent/daughter ratios in their sources as measured on samples. See Appendix DR2 (see text footnote 1) for data sources.

In northern Nicoya, lavas representing 56 m.y. of the Caribbean igneous province history crop out over a distance of <20 km, and those representing the entire 70 m.y. history of the province are within ~500 km. Accumulating 70 m.y. of igneous activity in the Caribbean, especially in a limited area, is difficult considering eastern Pacific plate motions of 5–10 cm/yr (Duncan and Hargraves, 1984; Engebretson et al., 1985; Pindell and Barrett, 1990), because the plate will move 3400–6800 km over this time span. It has been proposed that some of the igneous complexes along the Pacific margin of Central America contain accreted fragments of the paleo–Galápagos hotspot tracks, covering 45 m.y. (66–21 Ma) or more of the evolution of the Galápagos hotspot (Hoernle et al., 2002). Similarly, we propose that the belt of mafic igneous rocks extending from Guatemala (von Huene, 1989) to the Nicoya Peninsula previously formed the forearc of the Chortis subduction zone (Hauff et al., 2000a), and that it is made up of accreted portions of oceanic plateaus and hotspot tracks formed in the Pacific. It has also been proposed that the Central, Western, and Pacific Cordilleras in northwest South America (Colombia and Ecuador) are also accreted Pacific terranes (Kerr et al., 1997) with ages extending to 123 Ma (Lapierre et al., 2000). Albian–Aptian (97–125 Ma) lavas with plateau-type geochemical signatures have also been reported from Cuba (Kerr et al., 2000). Oceanic crust thickened by younger intraplate volcanism, e.g., forming oceanic plateaus and hotspot tracks, will be more buoyant and thus less likely to subduct than the surrounding oceanic crust. The Caribbean igneous province could have formed through accumulation of intraplate Pacific volcanic structures in the gap between the westward-moving Americas. Fragments of some of these structures are likely to have been accreted at the northern (Chortis block) and southern (northwest South America) edges of the gateway to the proto-Caribbean.

In conclusion, our study implies that the Caribbean large igneous province does not represent a single oceanic plateau, but instead consists of remnants of multiple smaller igneous structures (e.g., oceanic plateaus and paleo–hotspot tracks) formed over at least 56 m.y. (83–139 Ma), possibly overprinted by later in situ magmatism (69–78 Ma). The older igneous rocks at Nicoya, and possibly at other locations along the margins of the Caribbean province, could have been generated through large-volume pulsing of the Galápagos hotspot during its early history, making it one of the oldest active hotspots on Earth (at least 139 Ma), or through unrelated igneous events, derived from similar source materials. Other oceanic large igneous provinces may also represent the long-term accumulation and amalgamation of the products of intraplate volcanism through the subduction process, rather than a single, large-scale, but short-duration igneous event derived from a plume head at the initiation of a hotspot. Additional studies, combining modern age dating techniques with detailed geochemistry on the same igneous samples, are necessary to improve further our understanding of large igneous provinces.

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Notes