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Prolonged plume volcanism in the Caribbean Large Igneous Province: New insights from Curaçao and Haiti

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[1] We present 36 new ^{40}Ar-^{39}Ar incremental heating age determinations from the Caribbean Large Igneous Province (CLIP) providing evidence for extended periods of volcanic activity and suggest a new tectonomagmatic model for the province's timing and construction. These new ^{40}Ar-^{39}Ar ages for the Curaçao Lava Formation (CLF) and Haiti's Dumisseau Formation show evidence for active CLIP volcanism from 94 to 63 Ma. No clear changes in geochemical character are evident over this period. The CLF has trace element signatures (e.g., Zr/Nb = 10–20) and flat rare earth element (REE) trends consistent with plume volcanism. The Dumisseau Formation also has plume-like geochemistry and steeper REE trends similar to ocean island basalts. Volcanism in the Dumisseau Formation appears to have largely ceased by 83 Ma while at Curaçao it continued until 63 Ma. A rapidly surfacing and melting plume head alone does not fit this age distribution. Instead, we propose that the residual Galapagos plume head, following initial ocean plateau construction, was advected eastward by asthenospheric flow induced by subducting oceanic lithosphere. Slab rollback at the Lesser Antilles and Central America subduction zones created an extensional regime within the Caribbean plate. Mixing of plume with upwelling asthenospheric mantle provided a source for intermittent melting and eruption through the original plateau over a ~30 Ma period.

Components: 11,785 words, 7 figures, 2 tables.

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1. Introduction

[2] Large Igneous Provinces (LIPs) represent enormous volumes (>10^6 km^3) of mafic magmas, typically emplaced over geologically short intervals of a few million years [*Coffin and Eldholm*, 1994]. The Caribbean Large Igneous Province (CLIP) is a large submarine plateau thought to have been constructed initially as a LIP that now forms a thickened zone of oceanic crust between North America and South America [*Burke et al.*, 1984; *Duncan and Hargraves*, 1984]. LIPs are generally considered to form from melting related to a decompressing mantle plume head during the

initiation of hot spots [*Morgan*, 1981; *Richards et al*., 1989; *Campbell and Griffiths*, 1990; *Duncan and Richards*, 1991].

[3] Geochemical and geochronological evidence strongly associates the Galapagos hot spot with a ~95–90 Ma initiation of the CLIP. Originally formed in the eastern Pacific at the initiation of Galapagos mantle plume activity, the CLIP moved northeastward with the Farallon plate between the North and South American plates until collision with the Greater Antilles arc [*Burke et al*., 1984; *Duncan and Hargraves*, 1984; *Kerr et al*., 2003]. Volcanism can then be traced from the voluminous CLIP to the Galapagos Islands through a fragmentary 60 million year history partially preserved as accreted seamounts along the Central American coast and via the Cocos and Carnegie ridges [*Hoernle et al*., 2002; *Buchs et al*., 2011]. Isotopic domains present in the Galapagos Islands can be matched with similar compositional arrays observed in CLIP lavas [*Hauff et al*., 2000; *Geldmacher et al*., 2003; *Thompson et al*., 2003]. In addition, rare earth element (REE) patterns and mantle temperature calculations are consistent with melting from a mantle plume [*Sinton et al*., 1998; *Herzberg and Gazel*, 2009; *Hastie and Kerr*, 2010].

[4] Despite significant evidence for a mantle plume and a Pacific origin of the CLIP, a number of studies propose alternative models. *Pindell et al*. [2006] and *Wright and Wyld* [2011] suggest formation above a slab window with possible plume influence, and propose a much older age of CLIP initiation. Conflicting age estimations of CLIP lavas from the Curaçao Lava Formation (CLF) [*Beets*, 1972] highlight this controversy. ^{40}Ar-^{39}Ar ages of *Sinton et al*. [1998] at 89.5 Ma and 88 Ma from samples identified as the bottom and top of a 5 km submarine lava section described by *Klaver* [1987] suggest a relatively short emplacement period for the majority of lavas. Fossilized ammonites in one locality of intercalated sediments, however, have been identified as mid-Albian (~105 Ma) [*Wiedmann*, 1978]. Poikilitic sills and quartz-diorite plugs intruding the CLF have younger reported ages of 75 Ma (^{40}Ar-^{39}Ar whole rock) [*Sinton et al*., 1998] and 86 Ma (U-Pb zircon) [*Wright and Wyld*, 2011].

[5] Observations at CLIP localities north of Curaçao have led to a more consistent model of plume activity. The 1.5 km thick Dumisseau Formation of Haiti has previously reported radiometric ages of 94–88 Ma, in agreement with biostratigraphic data [*Sinton et al*., 1998]. At Beata Ridge, a fault-bounded monocline located just south of Haiti, a subseafloor sill complex is younger at 81–74 Ma [*Révillon et al*., 2000], lying below the plateau surface dated at 94–89 Ma [*Edgar and Saunders*, 1973; *Sinton et al*., 1998]. The light rare earth element (LREE) enriched character of the Dumisseau basalts compared with the more depleted Beata Ridge basalts led *Sinton et al*. [1998] and *Révillon et al*. [2000] to propose the older phase of activity was the result of initial plume volcanism and the younger phase was the result of extension and thinning of the plateau during interaction with the Greater Antilles subduction zone to the east.

[6] The aim of this paper is to present new high precision geochronology and geochemistry for the CLF, Curaçao and the Dumisseau Formation, Haiti. These two formations span a N-S transect of the CLIP and are perhaps the best exposures of internal structure and composition of the eastern portion of this ocean plateau. Combining our results with extensive geochronology already available for plateau rocks elsewhere in the Caribbean has allowed us to reexamine the tectonomagmatic origin of this submarine LIP.

2. Geologic Background

2.1. Curaçao

[7] The CLF forms much of the interior of the island of Curaçao, a tectonically uplifted part of the southern margin of the CLIP, located off the northern coast of Venezuela (Figure 1). It was first mapped by *Beets* [1972] as a late Cretaceous sequence of submarine lavas more than 1000 m thick, unconformably capped by sedimentary rocks of the Knip Group and Midden-Curaçao Formation. *Klaver* [1987] provided the first detailed study of the petrology of this formation. He proposed a 5 km section of submarine basalts ranging from picrites and olivine tholeiitic pillow basalts at the bottom of the sequence to plagioclase-clinopyroxene tholeiitic pillows, hyaloclastites, and poikilitic sills at the top. The variable thickness proposed for the CLF reported by these two studies reflects the highly weathered and discontinuous outcrops present on Curaçao making interpretation of the structural and stratigraphic relationships uncertain. The major, minor, and trace element geochemistry of these rocks was described in detail by both *Klaver* [1987] and *Kerr et al*. [1996], with both studies concluding that observed variations could be achieved by crystal

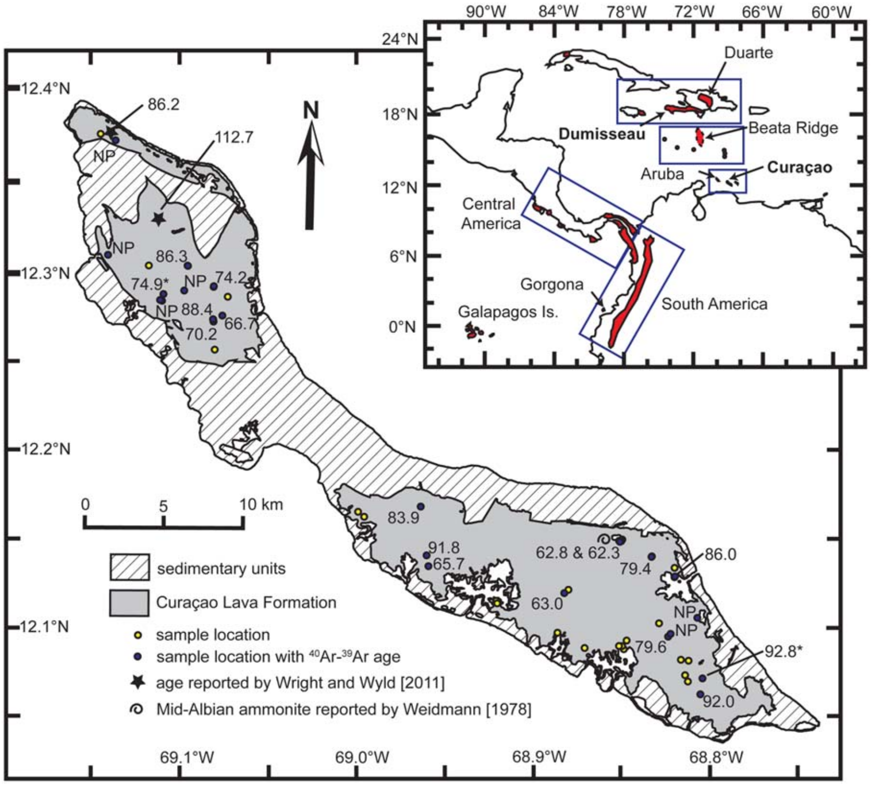

Figure 1. Overview map of prominent Caribbean Large Igneous Province exposures (inset) and simplified geologic map of Curaçao (modified after *Beets* [1972]). Sample locations along with age determinations (in Ma) are shown. The locations of 89.5 and 88.0 Ma ^{40}Ar-^{39}Ar ages reported by *Sinton et al*. [1998] are shown with asterisks as reanalyzed 92.8 Ma [*Snow et al*., 2005] and 74.9 Ma (this study) ages. The location of a 75.8 Ma age reported by *Sinton et al*. [1998] for a diabase sill is not known. Also shown are the locations of U-Pb ages reported in *Wright and Wyld* [2011; stars] and the location of a mid-Albian ammonite [*Wiedmann*, 1978]. NP denotes locations of analyzed samples with no plateau age. No clear age pattern is discernable in surface exposures as would be expected if previously proposed stratigraphic relationships were correct [see *Klaver*, 1987].

fractionation and/or accumulation from a common parental melt. Trace element and isotopic signatures are consistent with large degree melting of a plume-like mantle source, similar to conclusions reached from other Caribbean locations [*Kerr et al*., 1996; *Hauff et al*., 2000].

[8] Limited age constraints on CLF samples have provided inconsistent information. Ammonites from the only observed sediments intercalated with lava flows were identified as mid-Albian (~105 Ma) [*Wiedmann*, 1978], although the fossils were broken and highly deformed and could be reworked deposits [*Kerr et al*., 2003]. *Sinton et al*. [1998] analyzed three samples with identified ^{40}Ar-^{39}Ar plateau ages of 89.5 ± 1.0 and 88.0 ± 1.2 Ma from lavas at the top and bottom of the formation and a 75.8 ± 2.0 Ma age on a diabase sill. The oldest of these ages was reanalyzed by *Snow et al*. [2005] with a slightly older and more precise plateau age of 92.8 ± 0.5 Ma. These ages were consistent with the previously identified volcanic stratigraphy [*Klaver*, 1987], and consistent with an interpretation of rapid eruption of lava flows, based on the relative lack of intercalated sediments, followed by later intrusions. The most recent work on the island is less conclusive; *Wright and Wyld* [2011] reported a 86.2 ± 0.8 Ma U-Pb zircon age for a quartz diorite plug that intrudes the CLF at the north end of the island and *Humphrey* [2010] reported an older and less precise age of 112.7 ± 7.3 Ma from U-Pb dating of baddeleyite from a diabase sill, and suggested an older emplacement age for the CLF.

2.2. Dumisseau Formation, Haiti

[9] The Dumisseau Formation of Haiti is exposed by thrust and strike-slip faulting along the northern margin of the CLIP (Figure 1, inset). The formation consists of a 1.5 km section of massive and pillow basalt and picrite flows with intercalated pelagic limestones, siltstones, and turbidites, intruded by dolerite sills [*Maurrasse et al*., 1979].

Sen et al. [1988] showed that the geochemistry of the formation was typical of CLIP lavas found in the center of the Caribbean Plate from ocean drilling during DSDP Leg 15. Most samples have trace element signatures and isotopic compositions similar to other CLIP localities, although many samples show LREE enrichment more characteristic of ocean island basalts (OIB).

[10] *Sinton et al*. [1998] analyzed five whole rock samples from the Dumisseau Formation using ^{40}Ar-^{39}Ar incremental heating experiments and obtained plateau ages ranging from 96.2 ± 6.5 to 89.8 ± 1.1 Ma. These ages overlap the Coniacian to Turonian fossils (94–84 Ma) from interbedded sediments at the bottom of the Dumisseau Formation and are older than the late Santonian to early Campanian (84–80 Ma) fossils found in sedimentary interbeds at the top of the formation [*Maurrasse et al*., 1979]. Five additional samples were analyzed by *Snow et al*. [2005] with ^{40}Ar-^{39}Ar total fusion ages from 95.1 to 92.2 Ma although these analyses were all affected by significant ^{39}Ar recoil and did not develop age plateaus.

2.3. Beata Ridge and the Interior of the Caribbean Plate

[11] The CLIP has also been sampled in an intact central area of the Caribbean Plateau at the Beata Ridge and several Deep Sea Drilling Program (DSDP) and Ocean Drilling Program (ODP) sites [*Donnelly et al*., 1973; *Révillon et al*., 2000; *Sinton et al*., 2000; *Kerr et al*. 2009; Figure 1, inset]. Together, the Dumisseau Formation, CLF, and these central sites provide a N-S transect through the center of the Caribbean plateau and CLIP outcrops. Both the LREE enriched, OIB-like basalts of the Dumisseau Formation and flat REE patterns similar to those found in the CLF are found in the Beata Ridge and DSDP sites [*Sinton et al*., 1998; *Révillon et al*., 2000]. The oldest ages are found from DSDP Site 146 lavas: ^{40}Ar-^{39}Ar whole rock plateau ages of 90.6 ± 3.2, 92.1 ± 4.7, and 94.3 ± 2.8 Ma [*Sinton et al*., 1998]. At the Beata Ridge, where a thick sill complex was sampled by submersible, considerably younger ages were obtained for whole rock and plagioclase separates: nine plateau ages between 81 and 74 Ma, and two plateau ages at ~56 Ma [*Révillon et al*., 2000].

3. Sampling and Methodology

[12] Samples for this study were collected on the island of Curaçao in April 2010 and supplemented with samples previously described in *Kerr et al*. [1996] and *Klaver* [1987]. Coordinates for the collected samples are available in the online supporting information[1] while locations of previously studied samples are estimated from location maps provided within those references (Figure 1). Samples from the Dumisseau Formation, Haiti, were previously described in *Maurrasse et al*. [1979] and *Sen et al*. [1988].

[13] Age determinations for 22 samples from Curaçao and 14 samples from the Dumisseau Formation were derived from whole rock, groundmass, plagioclase, or glass separates. Whole rock samples consisted of 4 mm diameter minicores of the fresh and relatively phenocryst-free portions of rock fragments. The groundmass and plagioclase samples were crushed and sieved to a 200–300 or 400–500 μm size fraction and subjected to an extended acid leaching procedure following *Koppers et al*. [2000]. This consisted of 15 min sequential leaching in 1 N HCl, 5 N HCl, 1 N HNO_3, and 5 N HNO_3. Before irradiation, 50–100 mg of material was hand picked from the final leached separate. Whole rock and glass separates were not subjected to acid leaching. All samples were irradiated at the Oregon State University 1 MW TRIGA Reactor. Neutron flux was monitored using a Fish Canyon Tuff biotite (FCT-3) with a monitor age of 28.02 ± 0.16 Ma [*Renne et al*., 1998]. Argon extraction and analysis was achieved with a Merchantek 10 W CO_2 laser and an MAP-215-50 mass spectrometer following the methods outlined in *Duncan and Hogan* [1994] and *Duncan et al*. [1997]. Data reduction utilized ArArCALC v.2.2 [*Koppers*, 2002] using decay constants suggested by *Steiger and Jäger* [1977].

[14] Total fusion, plateau, and isochron ages are summarized for all analyzed samples in Tables 1 and 2. Total fusion ages incorporate all heating steps in a given incremental heating experiment and some step ages are clearly influenced by post-crystallization Ar-loss evident in the age spectra. Several samples are affected by redistribution of ^{39}Ar and ^{37}Ar atoms during neutron irradiation. This occurs in fine-grained rocks where ^{39}Ar from K-rich phases that generally release Ar at lower temperatures (e.g., clays, intersertal glassy matrix) transfers to K-poor phases that generally release Ar at higher temperatures (e.g., pyroxene, olivine), and ^{37}Ar transfers from relatively Ca-rich phases (e.g., feldspar, pyroxene) to Ca-poor phases (e.g.,

[1]Additional supporting information may be found in the online version of this article.

Table 1. ^{40}Ar-^{39}Ar Age Determinations for the Curaçao Lava Formation Lavas, Dikes and Hyaloclastites[a]

Sample	Material	Lithology	Total Fusion Age (Ma ± 2s)	Plateau Age (Ma ± 2s)	*N* Steps	MSWD	Probability (%)	Isochron Age (Ma ± 2s)	MSWD	$^{40}Ar/^{36}Ar$ (Initial ± 2s)	^{36}Ar (10^{-14} mol/g)	Age Spectrum Type
Cur-21i	gm	Lava flow	92.0 ± 1.5	92.0 ± 1.0	6/10	2.32	4	91.9 ± 1.0	2.42	295.9 ± 2.4	0.8	Plateau
Cao-40b	pl	Sill	91.5 ± 1.7	91.8 ± 2.1	7/7	1.72	11	90.5 ± 3.2	1.92	299.2 ± 8.7	2.3	Plateau
Cao-07	gl	Hyaloclastite	87.4 ± 2.3	88.4 ± 2.1	9/10	0.61	77	83.2 ± 22.9	0.72	319 ± 106	1.5	Plateau
Cao-35d	gl	Hyaloclastite	86.0 ± 2.8	86.3 ± 2.4	10/10	0.54	84	89.0 ± 6.1	0.47	278.6 ± 32.5	1.0	Plateau
Cao-13	pl	Sill	85.7 ± 3.0	86.0 ± 1.9	7/7	0.44	85	86.0 ± 1.9	0.47	295.1 ± 1.6	7.1	Plateau
Cao-18	pl	Sill	83.9 ± 1.7	83.9 ± 1.6	7/7	0.40	88	83.4 ± 2.1	0.41	296.5 ± 3.6	2.6	Plateau
Cao-14	pl	Sill	97.5 ± 3.0	79.4 ± 1.9	6/7	1.62	15	81.0 ± 8.6	1.83	291.7 ± 19.7	2.8	Plateau
79-Be-069	gm	Pillow lava	74.4 ± 4.6	79.6 ± 3.6	8/10	0.35	93	77.6 ± 6.1	0.33	296.5 ± 2.7	5.0	Plateau
BK-79–262	gm	Sill	73.7 ± 2.6	74.9 ± 2.1	10/10	0.78	63	77.8 ± 4.1	0.54	288.6 ± 8.1	4.9	Plateau
Cao-20	gm	Pillow lava	74.1 ± 2.3	74.2 ± 2.4	9/10	1.56	13	72.9 ± 2.5	1.19	298.8 ± 3.8	2.6	Plateau
Cao-04a	gm	Pillow lava	69.1 ± 1.2	70.2 ± 1.1	10/11	0.82	60	70.7 ± 2.5	0.89	294.0 ± 5.7	4.7	Plateau
Cao-03	gm	Lava flow	66.3 ± 0.9	66.7 ± 0.8	12/12	1.20	28	67.2 ± 1.2	1.18	294.3 ± 2.2	9.8	Plateau
BK-79–118	gm	Pillow lava	65.5 ± 2.9	65.7 ± 2.4	10/10	0.85	57	68.0 ± 3.8	0.64	293.8 ± 2.2	12.2	Plateau
Cur-10-02	gm	Pillow lava	62.6 ± 0.8	63.0 ± 1.0	10/12	1.91	5	63.8 ± 2.4	2.02	291.1 ± 10.7	3.1	Plateau
Cao-30	gm	Pillow lava	63.2 ± 1.0	62.8 ± 1.0	9/12	1.42	18	62.5 ± 2.1	1.61	296.2 ± 7.0	3.9	Plateau
Cao-10	gm	Pillow lava	60.1 ± 0.8	62.3 ± 0.8	8/12	1.74	9	64.6 ± 1.7	0.45	281.5 ± 9.0	2.6	Plateau
BK-79–183	gm	Pillow lava	53.4 ± 10.8	66.4 ± 10.7	5/9	0.38	83	71.0 ± 22.5	0.42	292.3 ± 13.0	1.6	Low^{39}Ar
BK-79–163	gm	Pillow lava	41.2 ± 2.9	None developed				None developed			23.3	Ar-loss
BK-79–263	gl	Hyaloclastite	53.1 ± 1.5	None developed				None developed			1.5	Ar-loss
Cao-32	gm	Lava flow	118.0 ± 3.5	None developed				None developed			0.4	Recoil
Cao-22	gm	Lava flow	72.4 ± 0.5	None developed				None developed			2.0	Recoil
Cao-21	gm	Lava flow	61.2 ± 0.7	None developed				None developed			4.8	Recoil

[a]Ages calculated using biotite monitor FCT-3 (28.02 Ma) [*Renne et al.*, 1998] and the total decay constant $\lambda = 5.530 \times 10^{-10}$/yr [*Steiger and Jäger*, 1977]. *N* is the number of heating steps (defining plateau/total); MSWD is an *F* statistic that compares the variance within step ages with the variance about the plateau age. Material abbreviations are gl = glass, gm = groundmass, pl = plagioclase, and wr = whole rock. Sample BK-79–183 and below are not considered reliable plateau ages due to low proportions of total ^{39}Ar (<70%) in the plateau, unusually high uncertainty on individual heating steps, or an MSWD > 3, although some useful age information may be found in the total fusion or isochron ages.

Table 2. ^{40}Ar-^{39}Ar Age Determinations for Dumisseau Formation Lavas and Sills[a]

Sample	Material	Total Fusion Age (Ma ± 2s)	Plateau Age (Ma ± 2s)	N Steps	MSWD	Probability (%)	Isochron Age (Ma ± 2s)	MSWD	$^{40}Ar/^{36}Ar$ (Initial ± 2s)	^{36}Ar (10^{-14} mol/g)	Age Spectrum Type
HA-77–109	gm	95.4 ± 2.1	93.6 ± 1.8	9/9	1.90	6	92.5 ± 1.8	1.20	300.6 ± 4.6	4.0	Plateau
HA-77–170	pl	92.7 ± 2.1	90.8 ± 1.8	7/8	0.24	96	90.2 ± 2.1	0.08	298.0 ± 4.7	5.0	Plateau
HA-77–29	pl	88.7 ± 1.2	88.0 ± 1.2	13/13	1.58	9	87.1 ± 1.1	0.80	310.1 ± 8.9	2.4	Plateau
HA-76–28	pl	87.7 ± 1.2	87.1 ± 1.1	7/8	0.45	84	86.9 ± 1.2	0.54	297.8 ± 10.5	1.3	Plateau
HA-77–144	pl	86.8 ± 0.8	86.8 ± 0.7	10/10	0.14	100	86.9 ± 0.8	0.15	293.1 ± 18.5	1.0	Plateau
HA-77–178	pl	86.4 ± 1.2	86.0 ± 1.1	8/8	0.45	87	85.5 ± 1.2	0.22	302.5 ± 10.7	1.8	Plateau
HA-77–244	pl	86.0 ± 1.4	85.2 ± 1.1	9/9	0.54	83	84.9 ± 1.2	0.2	299.4 ± 4.6	3.6	Plateau
HA-77–159	wr	75.8 ± 0.8	82.8 ± 0.7	7/10	1.52	17	83.4 ± 0.9	1.03	286.7 ± 9.7	2.8	Plateau
HA-77–62	pl	105.2 ± 6.0	105.0 ± 5.3	13/13	1.09	36	100.8 ± 7.2	1.06	298.4 ± 4.1	5.4	Low^{39}Ar
HA-76–117	wr	91.1 ± 0.7	85.5 ± 0.7	6/10	1.02	40	85.2 ± 0.9	0.89	300.4 ± 8.7	2.3	Recoil
HA-77–237	gm	89.8 ± 1.1	86.1 ± 0.8	4/9	1.24	29	86.4 ± 3.9	1.24	292.0 ± 49.0	3.2	Recoil
HA-77–245	wr	77.7 ± 1.1	None developed				None developed			28.3	Ar-loss
HA-77–110	gm	90.5 ± 1.8	None developed				None developed			4.8	Recoil
HA-77–164	wr	91.0 ± 0.6	None developed				None developed			5.0	Recoil

[a]See Table 1 for full explanation. Sample HA-77-62 and below are not considered reliable plateau ages.

clays, intersertal glassy matrix). These so-called recoil effects produce erroneously old ages at low temperature steps and erroneously young ages at high temperature steps resulting in descending step ages with gas release ("inverse staircase" age spectra). In such cases, and where there is no evidence for ^{40}Ar-loss (in low temperature steps), the total fusion ages are equivalent to K-Ar ages. Isochron ages are calculated from the slopes of linear regressions through the step isotopic compositions ($^{40}Ar/^{36}Ar$ versus $^{39}Ar/^{36}Ar$) and make no assumption about the initial Ar composition ($^{40}Ar/^{36}Ar$). Because the step compositions do not typically show large dispersion, the analytical uncertainties for isochron ages are larger than for corresponding plateau ages.

[15] All age spectra were examined for evidence of disturbance, namely, ^{40}Ar-loss (at lower temperature heating steps), and recoil. Conventionally, plateau ages are considered reliable if they include three or more contiguous step ages constituting >50% of the total gas released. A statistical parameter, mean square of weighted deviations (MSWD), compares error within step ages with scatter about the mean step age, and has a 2σ (95%) confidence limit below about 2.5 (depending on the number of heating steps). The probability, p, combines MSWD and number of heating steps in a chi-square statistic that expresses the level of confidence that the plateau-forming step ages define a meaningful age. Values equal to or greater than 5% (95% confidence) indicate statically meaningful ages.

[16] Our analyzed samples show evidence for low temperature alteration, exposure to seawater, and subaerial weathering. In such cases, the possibility for ^{40}Ar-loss and K-addition during fluid-rock chemical exchange is significant. *Baksi* [2007] compared fresh and altered basalts dated by ^{40}Ar-^{39}Ar incremental heating experiments and developed several quantitative measures of levels of alteration at which age data may be compromised. The first is the concentration of ^{36}Ar (atmospheric, corrected for reactor produced ^{36}Ar from Ca), which lies below about 3×10^{-14} mol/g for whole rock basalts and 10×10^{-14} mol/g for plagioclase in samples that produced acceptable (crystallization) plateau ages. Another parameter, the "alteration index," calculated from $^{36}Ar/^{39}Ar$, also relates the amount of atmospheric-derived Ar to intrinsic K-content, has a threshold value of <0.0006 for acceptable ages.

[17] New major, minor, and trace element geochemical analyses were performed on whole

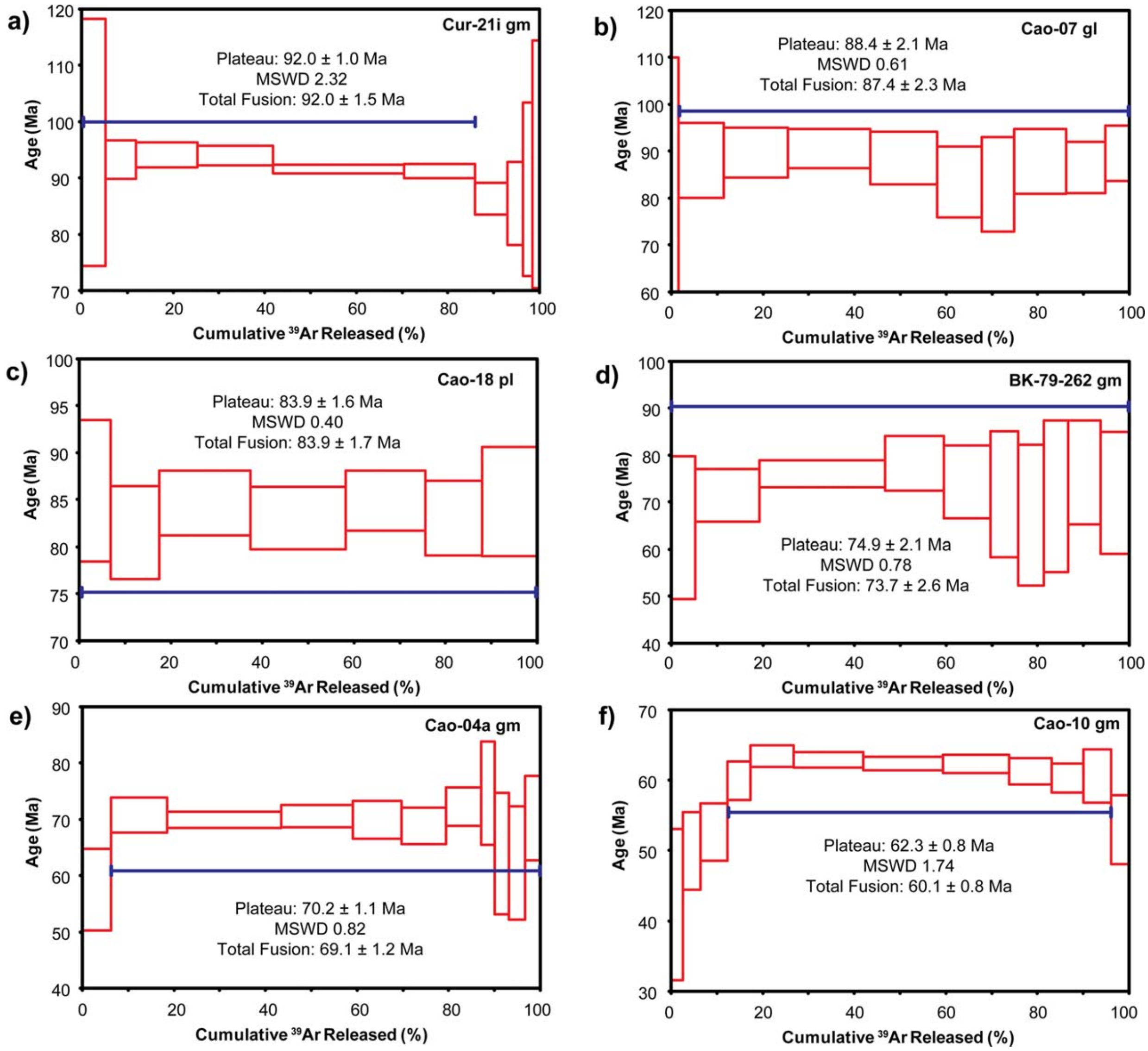

Figure 2. Selected age spectra from the Curaçao Lava Formation. All samples shown have well-defined age plateaus and are considered reliable estimates of the crystallization age. Samples shown range from 92 to 63 Ma with no clear evidence of a hiatus in volcanic activity.

rocks. Major and minor elements were analyzed by X-Ray Fluorescence (XRF) for the Curaçao samples at Pomona College and for the Dumisseau Formation at Washington State University (WSU) Geoanalytical Lab. All whole rock trace element data were obtained at WSU using Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). Sample preparation involved selecting visually unaltered chips of rock and powdering the samples in a W-Carbide shatterbox, mixing with Li-tetraborate flux, and fusing, following the general procedure outlined in *Johnson et al*. [1999]. ICP-MS samples were also dissolved in acid prior to analysis following WSU's standard procedure [*Knaack et al*., 1994]. In addition to whole rock analyses, hyaloclastite samples from Curaçao were analyzed by Electron Microprobe Analysis (EMPA) at the University of Oklahoma and laser ablation-ICP-MS (LA-ICP-MS) at Oregon State University, using the methodology described in *Loewen and Kent* [2012].

4. Results

4.1. Curaçao Geochronology

[18] Of the 22 dated samples from Curaçao, 16 provided reliable plateau ages ranging from 92 to

63 Ma (Table 1). In all cases, plateau ages are consistent with isochron ages and show no evidence for significant recoil, or ^{40}Ar-loss (Figure 2). Within this age range, there are samples with ages grouped at 92 Ma, 88–84 Ma, 80–75 Ma, and 70–63 Ma (Figure 2). This broad age range does not fit with that expected from the volcanic stratigraphy described by *Klaver* [1987; Figure 1] and earlier age determinations of *Sinton et al*. [1998]. Below we discuss each of the age groupings. Isochron and plateau diagrams for all analyzed samples are available in the online supporting information; full data files used for age calculations, including tables and plots, can be accessed at the online database http://earthref.org.

[19] The oldest ages are 92.0 ± 1.0 Ma from a groundmass separate of basaltic lava collected by *Kerr et al*. [1996] and 91.8 ± 2.1 Ma from a plagioclase separate from a plagioclase-clinopyroxene poikilitic sill. The groundmass sample exhibited a very slight recoil age spectrum, with MSWD just outside the 95% confidence limit, but with six heating steps that encompassed over 80% of the total ^{39}Ar released used in the plateau calculation (Figure 2a). The plagioclase separate returned a plateau with no evidence of recoil or ^{40}Ar-loss, but low proportions of radiogenic ^{40}Ar resulted in higher uncertainty on individual steps and the plateau age. Both samples are located on the southeast end of the island and very near a sample with previously reported plateau ages of 89.5 ± 1.0 Ma and 92.8 ± 0.5 Ma [*Sinton et al*., 1998; *Snow et al*., 2005; Figure 1].

[20] Glass separates from hyaloclastite units (Cao-07 and Cao-35d) returned ages between 88 and 86 Ma (Figure 2b). Both of these deposits are on the northwest end of the island adjacent to significantly younger lavas. Hyaloclastites from the southeast end of the island are generally more altered, and the one attempted age on a glass separate from this region (BK-79–263) exhibited an ^{40}Ar-loss profile from which no reliable age could be determined (Table 1, supporting information).

[21] Plagioclase separates from two poikilitic sills (Cao-13 and Cao-18) in the southeast returned good plateaus between 86 and 83 Ma (Figure 2c). While petrographically and geochemically similar to the 92 Ma plagioclase separate, these two samples were near the northern extent of CLF outcrops and could represent a stratigraphically younger position according to *Klaver* [1987]. Sill rock Cao-14 (plagioclase separate) produced a reasonable 79.4 ± 1.9 Ma plateau profile comprising about 70% of the gas released and passes all criteria for age reliability. However, it is petrographically similar to and less than 2 km away from the 86 Ma sill sample (Figure 1).

[22] A number of groundmass separates from plagioclase-clinopyroxene-bearing lavas display a range of plateau ages from 80 to 63 Ma (Figures 2d–2f). Several of these samples with excellent plateau profiles are found near sill and hyaloclastite samples with significantly older ages. One 74.9 ± 2.1 Ma sample (BK-79–262) is a reanalyzed groundmass portion of an 88.0 ± 1.2 Ma whole rock analysis [*Sinton et al*., 1998], suggesting the possibility that phenocryst phases (olivine ± clinopyroxene) may retain mantle-derived ^{40}Ar (Figure 2d). The youngest of these samples are directly adjacent to the mid-Albian ammonite fossil locality described by *Wiedmann* [1978; Figure 2f].

[23] Quantitative measures of alteration proposed by *Baksi* [2007] have been calculated from the isotopic data. In general, ^{36}Ar concentrations are below the suggested cutoff values for whole rocks and plagioclase separates (Table 1). Sample BK-79–163 has a much higher ^{36}Ar concentration (28.3×10^{-14} mol/g), consistent with the observed significant ^{40}Ar-loss. Samples BK-79–118 and Cao-03 have slightly high ^{36}Ar concentrations, but statistically acceptable plateaus and isochrons, and ages that are not dissimilar to those of other less altered rocks. The alteration index values for Curaçao samples are high, 0.02–0.5, and we believe this reflects the very low K-contents of these rocks, rather than high concentrations of ^{36}Ar. We feel that this parameter is not appropriate for evaluating age quality in such compositions.

4.2. Dumisseau Formation Geochronology

[24] Samples from the Dumisseau Formation, Haiti, exhibit a smaller age range, and overlap the older ages from Curaçao. We consider 8 of the 14 analyzed samples to have reliable plateau ages, while the others are compromised by recoil or ^{40}Ar-loss patterns (Table 2). The oldest plateau ages are 94–90 Ma (Figure 3a), while the youngest is 83 Ma (Figure 3b). With the exception of this youngest age, uncertainties on all of the other plateau ages are overlapping and yield no conclusive evidence for a hiatus in activity (Figures 3b and 3c). In addition to the statistical criteria (MSWD, $p > 5\%$) for acceptable plateaus, these samples also exhibit low concentrations of ^{36}Ar, consistent with their petrographically fresh appearance. The one exception is

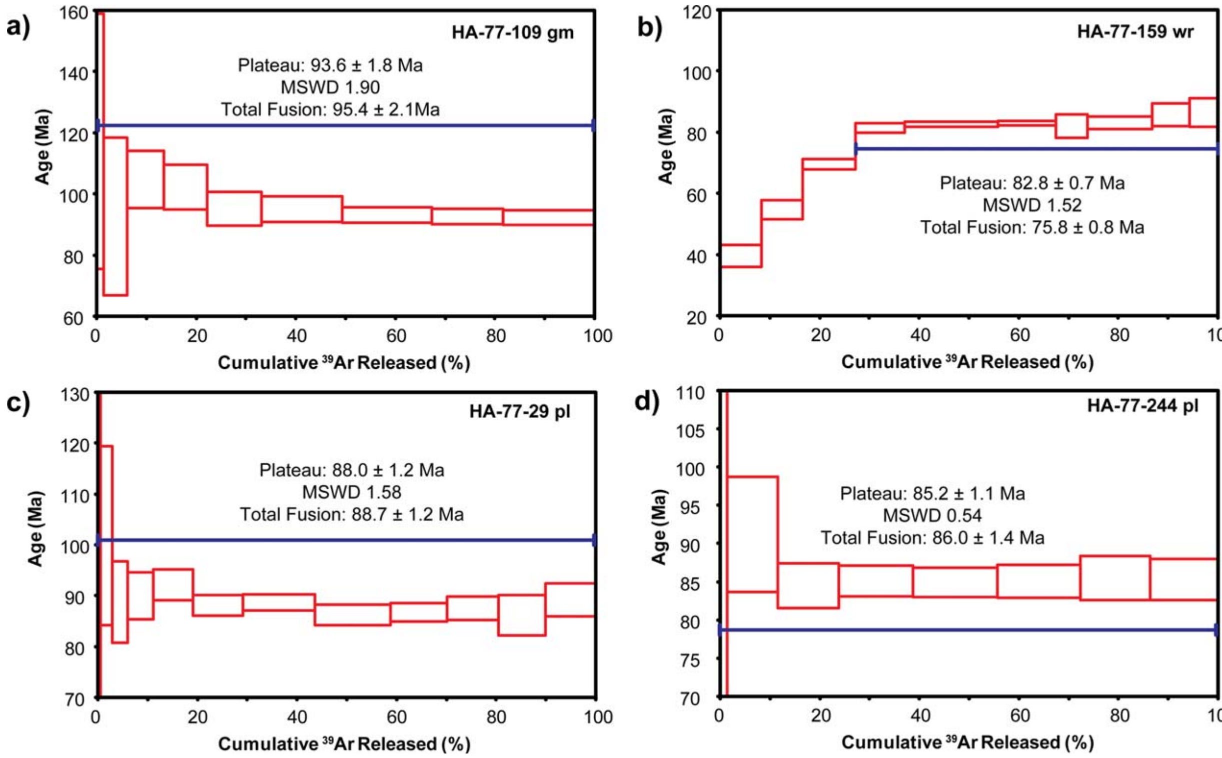

Figure 3. Selected age spectra from Dumisseau Formation. Samples with well-defined plateau profiles are shown for ages between 94 and 83 Ma, although the youngest of these ((b) HA-77–159) shows some evidence for ^{40}Ar-loss from low temperature steps.

HA-77–245, which has a very high ^{36}Ar content and displays an ^{40}Ar-loss age spectrum.

4.3. Geochemistry

[25] We use trace element analyses of all dated samples to compare the geochemical character across the broad age range, and with that of the entire CLIP. Major elements were also analyzed and are consistent with previous work, demonstrating that the chemistry of most samples can be modeled as olivine ± clinopyroxene and plagioclase cumulates or fractionates from parental melts of similar composition [*Klaver*, 1987; *Kerr et al*., 1996].

[26] Trace element signatures of the CLF are broadly consistent with other CLIP localities. Rare earth element profiles are generally flat (normalized to chondritic values) [*McDonough and Sun*, 1995; Figure 4]. Elemental ratios associated with plume sources, such as Zr/Nb, are lower (10–20) than typical mid-ocean ridge basalt (MORB, Zr/Nb > 30) and on the plot of Nb/Y versus Zr/Y shown in Figure 5 almost all CLF samples plot well within the plume-associated Icelandic Array of *Fitton et al*. [1997]. Mafic samples have Ba/Nb < 10, although more felsic intrusions in the NW corner of the island as well as nearby basalts (Cao-22) are more arc like with Ba/Nb > 50, similar to analyses of the coeval Aruba Batholith [*White et al*., 1999; Figure 6]. While Ba may be sensitive to hydrothermal alteration, La/Nb, which is less susceptible to low temperature chemical exchange, shows the same trend. All anomalously high Ba/Nb also having high La/Nb but most CLF samples having La/Nb < 1 (Figure 6).

[27] The Dumisseau Formation samples have similar major element chemistry to the other lavas described above, but contrast with CLF lavas in that they exhibit LREE enriched patterns (Figure 4). Other trace element concentrations are also higher, such as Ti, Zr, Nb, Sr, Hf, Ta, Th, and U. Overall, trace element contents of Dumisseau Formation lavas are more similar to typical ocean island basalts (OIB).

4.4. Isotopes

[28] Extensive whole rock isotopic work has been conducted on Curaçao by *Kerr et al*. [1996], *Walker et al*. [1999], *Hauff et al*. [2000], *Geldmacher et al*. [2003], and *White et al*. [1999], while Sr-Nd isotopic analyses have been reported for the Dumisseau

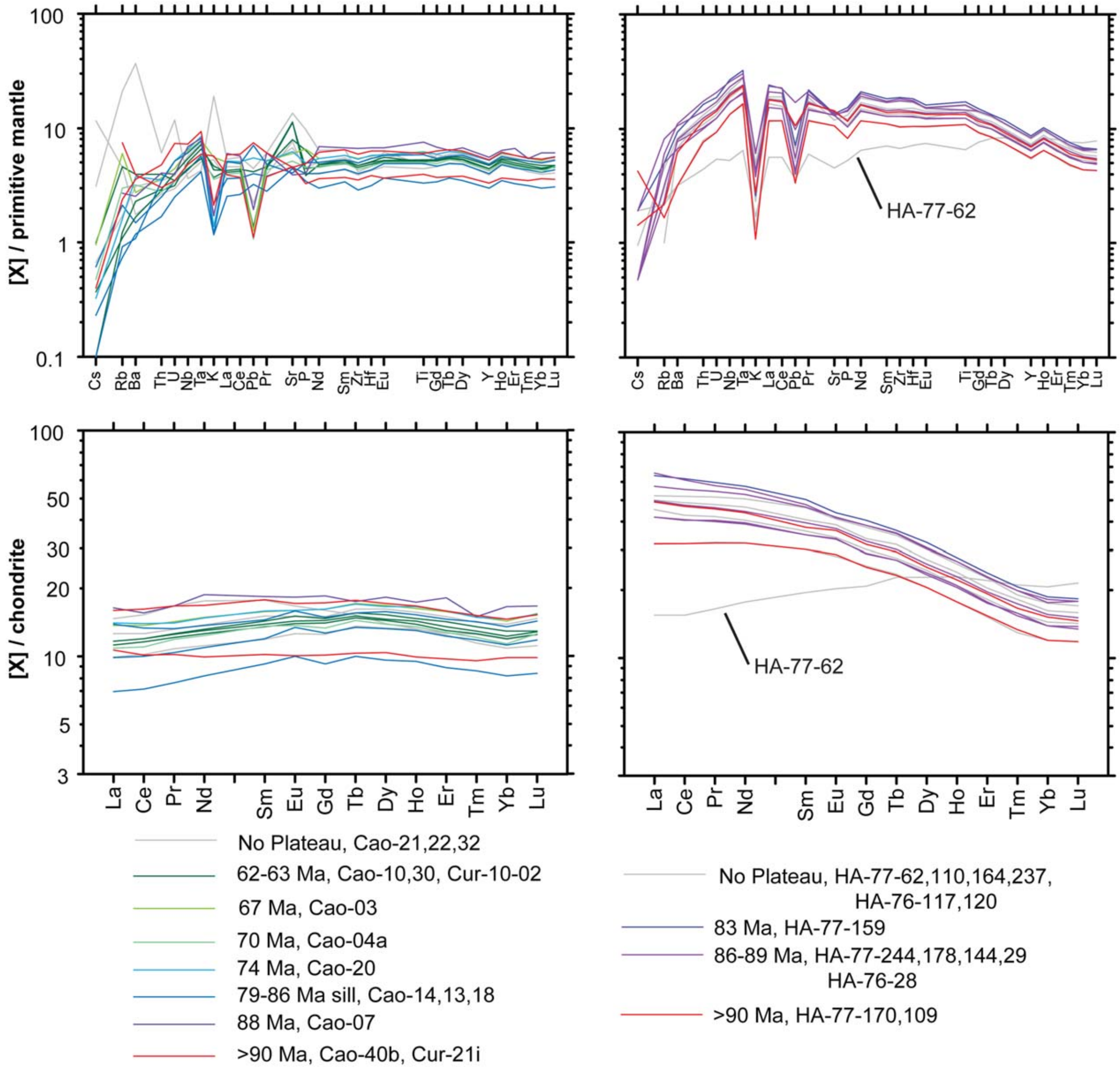

Figure 4. Multielement diagrams for samples from the CLF and Dumisseau Formation. Notable anomalies include low K and Pb in all Dumisseau Formation samples and most Curaçao samples. Samples with minimal K anomaly also have high Sr possibly due to greater alteration of these samples, although other fluid-mobile elements such as Cs, Ba, and U are not enriched. Curaçao samples have mostly flat REE profiles, while Dumisseau Formation samples have notably higher LREE concentrations with the exception of HA-77-62.

Formation by *Sen et al*. [1988]. Although these compositions were not on the same samples for which we have age determinations, they likely sample similar units. These studies all concluded that isotopic values are consistent with melting from plume-influenced mantle sources with similar end-members as those contributing to the current Galapagos hot spot. We report one new He isotopic analysis of an olivine separate from a Dumisseau Formation picrite (HA-77-34), which produced an $R_a/R = 12.4 \pm .21$ (2σ) within the range of high values obtained from Gorgona and Galapagos [*Révillon et al*., 2002; *Kurz et al*., 2009]. These values are all higher than expected for MORB mantle ($R_a/R = 8$–10) and at the low range expected for a plume source [*Graham*, 2002].

5. Discussion

5.1. Geologic History of Curaçao

[29] Our new ^{40}Ar-^{39}Ar age determinations require a revision of models for the formation of the CLF.

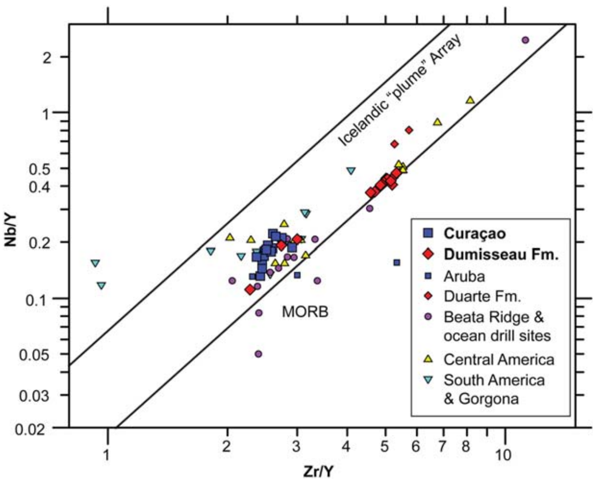

Figure 5. Plume and MOR-derived basalts can be differentiated on a plot of Zr/Y and Nb/Y as shown by *Fitton et al.* [1997] with samples from Iceland. Here, trace elements for the CLF and the Dumisseau Formation are compared to regional samples from throughout the Caribbean Large Igneous Province with reported ^{40}Ar-^{39}Ar age determinations [*Alvarado et al.*, 1997; *Kerr et al.*, 1997; *Sinton and Duncan*, 1997; *Sinton et al.*, 1998; *Lapierre et al.*, 1999; *White et al.*, 1999; *Révillon et al.*, 2000; *Sinton et al.*, 2000; *Hoernle et al.*, 2002, 2004; *Escuder-Viruete et al.*, 2011; *Serrano et al.*, 2011]. Rocks from the CLIP consistently plot within the plume portion of this array, consistent with previous isotopic studies and other trace element ratios (e.g., Zr/Nb, Figure 6).

In contrast to earlier studies, which argued for rapid formation [*Klaver*, 1987; *Sinton et al.*, 1998], our data show a more extended geologic history for the sequence. Magmatism occurred from 92 to 63 Ma with no clear evidence for breaks in volcanic activity during this period (Figure 2). These results have several important implications: (1) The volcanic stratigraphy of Curaçao consists of multiple volcanic pulses despite a lack of observed erosional horizons or sedimentary interbeds; (2) the CLF did not form prior to 95 Ma as other workers have proposed [*Wiedmann*, 1978; *Wright and Wyld*, 2011]; and (3) the lavas of the CLF were not emplaced in a short 1–5 million year duration typical of LIPs worldwide [*Coffin and Eldholm*, 1994; *Sinton et al.*, 1998]. Consequently, despite virtually uniform major, minor, and trace element patterns [*Klaver*, 1987; *Kerr et al.*, 1996], the Curaçao lavas appear to represent continuous or intermittent magma generation from a broadly similar mantle source over a period of ~30 million years.

[30] Our new data and observations argue that the stratigraphy of the island is more complex than the relatively simple sequences presented by *Klaver* [1987] and *Beets* [1972]. As shown in Figure 1, there is no systematic change in age across the island. In addition, intrusive rocks (sills and plugs) yield ages that span the first half of the volcanic history (Table 1). This includes ages from plagioclase separated from poikilitic sills in the southeast end of Curaçao and zircon separated from intrusive plugs in the northwest end of the island [*Wright and Wyld*, 2011]. Field exposures are insufficient to determine the relationships between outcrops separated by flat areas covered by soil and vegetation. We suggest that the internal structure of the CLF is a sequence of hyaloclastites, pillow and massive lava flows, and sills, which have been gently folded and offset by WNW-ESE faulting. In our field sampling, we did not observe evidence for the simple stratigraphic sections proposed by *Beets* [1972] or *Klaver* [1987]. The second of these studies determined some of the structural orientations on Curaçao by measuring the bedding of pillow lavas. This method, however, can be problematic since observations of recent pillow lava flows often show chaotic and steep-sided flow fronts [*Jones*, 1968; *Moore*, 1975]. The complex nature of submarine lava flows coupled with the extensively weathered and discontinuous outcrops within the CLF, low relief, and similarity of rock types, leads us to conclude that previous stratigraphic reconstructions did not observe the unconformities between volcanic sequences or faulted sections implied by the age range of our data.

[31] Similarly, some reconciliation is required between the younger ages identified in the CLF and previous estimates of the age of overlying sedimentary units. The Knip Group is unconformably separated from the CLF by a distinct brecciated soil horizon and is estimated to be Campanian to Maastrichtian in age (~84–66 Ma) [*Beets*, 1972, 1977]. Recent U-Pb dating of detrital zircon grains and ^{40}Ar-^{39}Ar detrital hornblende of both continental and island arc origin return a maximum age of ~74 Ma for these sediments [*Wright and Wyld*, 2011]. Our new ages suggest that four lava flows of the CLF are broadly coeval (66–63 Ma) with the Knip Group sediments. We note, however, that the sediments accumulated rapidly (>1 km thickness suggested for the Knip Group in NW Curaçao, in ~8 m.y.), while there is minimal evidence for sediments within the CLF over 30 m.y. of intermittent volcanic activity.

[32] Several key field relationships could help explain the occurrence of young lava flows

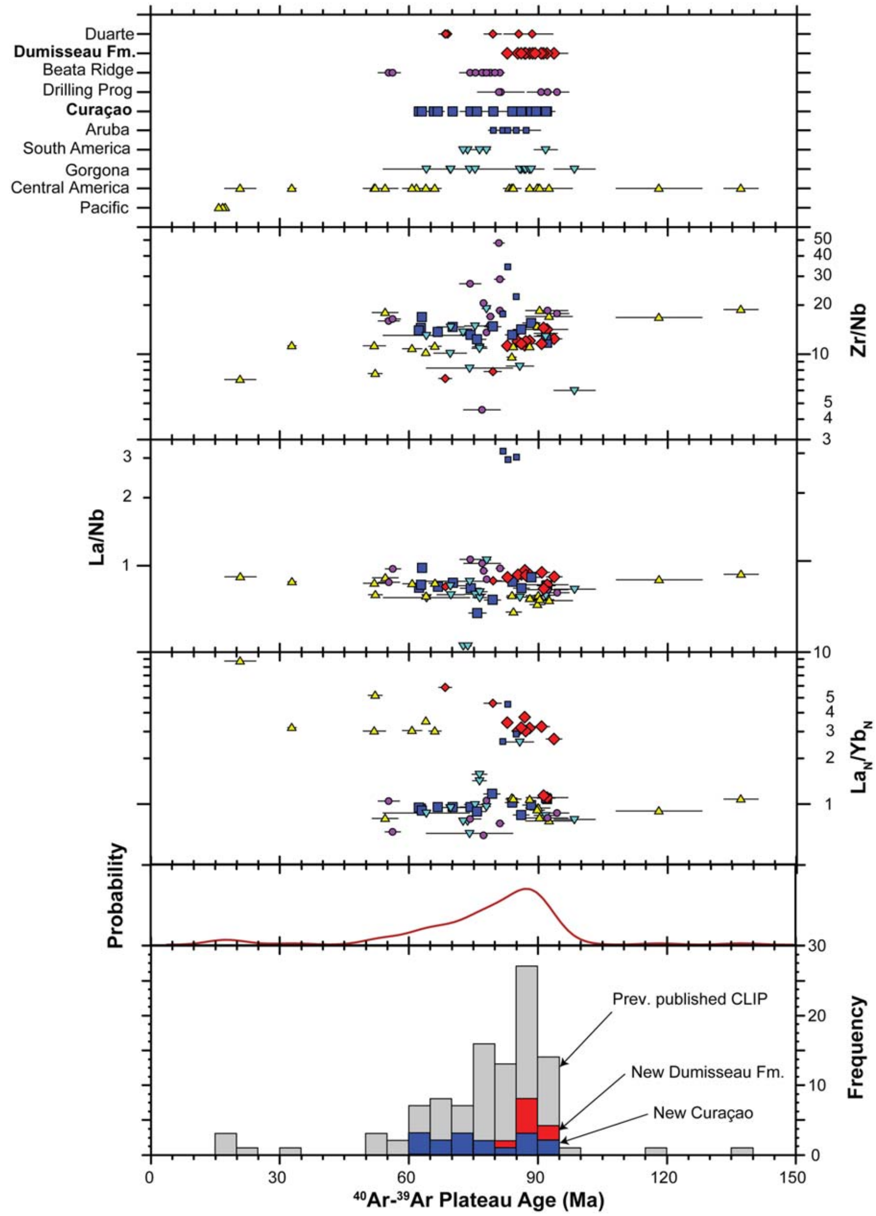

Figure 6. ^{40}Ar-^{39}Ar plateau ages determined in this study and previous work (see Figure 5 for references). A histogram fitted with a Kernel Density Estimation [*Vermeesch*, 2012] shows clear evidence that CLIP volcanism began 90–95 Ma and largely ceased by 60 Ma. Samples from the CLF (shown in blue) span this range and are representative of Caribbean-wide activity, while samples from the Dumisseau Formation (shown in red) are present only during the first 10–15 million years of activity. A few samples <50 Ma from the western margin of Central America are interpreted as accreted seamounts from the Galapagos hot spot trail, and also display distinctive trace element signatures.

(without intercalated sediments) erupted within the time frame of Knip Group sedimentation. (1) Unrecognized faulting may form some contacts of the CLF. The collision of the Caribbean Plate and South America has resulted in regional right-lateral transform motion. The extreme NW outcrops of the CLF are geochemically distinct from lavas found elsewhere on Curaçao and are similar to samples from the island of Aruba located nearby to the NW. Deconstruction of right-lateral motion could move this portion of the CLF closer to Aruba. (2) Erosional unconformities occur between the CLF and Knip Group and between the Knip Group and younger sedimentary units [*Beets*, 1972]. The thickness of the Knip Group is also variable, with thick sequences in the NW pinching out to the SE. (3) The CLF is exposed in two NW-trending anticlinoria occupying the elliptical NW and SE highlands of the island, separated by a syncline in the center of Curaçao. Although previous work suggests these structures developed in the early Tertiary [*Beets*, 1972], considerable deformation occurred on Aruba at the same time as younger CLF lavas erupted [*Wright and Wyld*, 2011]. If some of the folding began to occur during the late Cretaceous, the young CLF lavas would have erupted on uplifting regions while CLF lavas with intercalated sediments are hidden below the surface in the syncline. Hence, the anticlinal crests may have been at or above sea level at the time of Knip Group sedimentation. Given the poor exposure of outcrops on Curaçao, these new age determinations should provide motivation to consider alternate interpretations of the geologic structure of the island.

[33] Our results contradict the recent interpretation by *Wright and Wyld* [2011] that the CLF formed earlier than 95 Ma. Their work rejected previous ^{40}Ar-^{39}Ar geochronology [*Sinton et al.*, 1998] in favor of an imprecise U-Pb microbadellyite age [*Humphrey*, 2010] and an early identification of broken and highly deformed mid-Albian ammonites in intercalated sediments [*Wiedmann*, 1978]. The large number of new ^{40}Ar-^{39}Ar ages presented here provides compelling evidence that the CLF formed after 95 Ma, with lavas adjacent to the ammonite locality returning the youngest ages (Figure 1). These results also show that instead of two distinct magmatic events proposed by *Sinton et al.* [1998], volcanism was intermittent throughout the 30 Ma development of the CLF.

[34] We also observe similar major, minor, and trace element compositions in our CLF samples through time. These systematic geochemical patterns cannot be the result of the evolution of a single magma batch over a 30 million year time span. Instead, the compositional similarities between samples of different ages require a similar mantle source for melting and common petrogenic processes acting over the time interval from $\sim$92–63 Ma. Trace element ratios such as Zr/Nb or La/Nb (Figure 6) require that the melt source region is similar in composition through time, and relatively tight major element trends [*Kerr et al.*, 1996] suggest magma batches follow comparable paths of compositional modification (olivine fractionation or accumulation followed by clinopyroxene and plagioclase fractionation). A notable exception may be the geochemistry of the picrites, which have notably lower εNd [*Kerr et al.*, 1996]. These samples could not be directly dated due to low potassium contents and heavy alteration. Their occurrence on the SE end of Curaçao [*Klaver*, 1987] associates them with the oldest samples we have dated and is consistent with high temperature magmatism expected with the initial impingement of a mantle plume [*Hastie and Kerr*, 2010].

5.2. Geologic History of the Dumisseau Formation

[35] Our new ages fall largely within the expected range of previous radiometric dating on the Dumisseau Formation [*Sinton et al.*, 1998; *Snow et al.*, 2005] and fossil assemblages identified in interbedded sediments [*Maurrasse et al.*, 1979]. Only 10 million years of volcanism is evident here compared with 30 million years on Curaçao, although the earliest lavas of both formations are 93–92 Ma. This initial age is consistent with the earliest samples from most other CLIP localities (Figure 6) and Turonian to early Coniacian fossil age estimates of interbedded sediments in the lowest sections of the Dumisseau Formation. Late Santonian to early Campanian fossils in the basalts from near the top of the Dumisseau Formation match our youngest radiometric ages (82.8 $\pm$ 0.7 Ma).

[36] Geochemically, the Dumisseau Formation is distinct from the Curaçao lavas with $La_N/Yb_N > 3$ (Figure 6), and these differences can most easily be related to lower degrees melting of a plume-influenced mantle source. Trace element ratios that change by smaller amounts with degree of melting but largely reflect source character (e.g., Zr/Nb) are similar to the CLF.

5.3. Timing and Geochemistry of Volcanism Across the CLIP

[37] The age range and geochemical character of samples from the CLF and the Dumisseau Formation exemplify the broader character and timing of the CLIP. We compare our new age and trace element geochemistry with additional published plateau ages from throughout the Caribbean in Figures 5 and 6 [*Alvarado et al.*, 1997; *Kerr et al.*, 1997; *Sinton and Duncan*, 1997; *Sinton et al.*, 1998; *Lapierre et al.*, 1999; *White et al.*, 1999; *Révillon et al.*, 2000; *Sinton et al.*, 2000; *Hoernle et al.*, 2002, 2004; *Escuder-Viruete et al.*, 2011; *Serrano et al.*, 2011]. We have restricted our consideration to samples with well-constrained plateau ages. Figure 6 shows that CLIP volcanism on Haiti and Curaçao, bracketing the eastern CLIP, commenced between 95 and 90 Ma. Volcanism waned in the northern CLIP localities after $\sim$10 million years but continued in the southern

Caribbean and Central American CLIP localities until approximately 60 Ma. After this time, geochemically related volcanic activity is found in accreted seamounts on the Pacific coast of Central America associated with the trail of the Galapagos hot spot [*Hoernle et al*., 2002].

[38] In addition to covering the span of CLIP volcanism, CLF and Dumisseau Formation lavas include some of the earliest examples of CLIP volcanism. Our oldest dated samples (93.6 ± 1.8 Ma for the Dumisseau Formation and 92.0 ± 1.0 Ma for the CLF) are also among the earliest ages reported for the entire CLIP (Figure 6). The only older ages are 94.3 ± 2.8 Ma from DSDP Leg 15 located in the middle of the Caribbean plate [*Sinton et al*., 1998] and 98.4 ± 2.4 Ma from Gorgona Island [*Serrano et al*., 2011]. Two considerably older ages reported from *Hoernle et al*. [2004; 137 ± 2 and 118.2 ± 1.8 Ma] are limited in occurrence to the Nicoya Peninsula, Costa Rica, which may represent preexisting oceanic crust of the Farallon plate. The abundance of basalt crystallization ages from throughout the CLIP starting after 95 Ma and the relative absence of ages before this time strongly support this time as the initiation of plume volcanism which continues today in the Galapagos hot spot.

[39] The trace element signature of the vast majority of CLIP samples is that of a plume source. Ba/Nb is generally < 10 and La/Nb < 1, suggesting no substantial subduction influence, and Zr/Nb = 10–20, excluding a typical MORB depleted mantle source (Figure 6). Samples also plot clearly within the plume-sourced "Iceland Array" as opposed to the MORB field of *Fitton et al*. [1997; Figure 5]. The CLF samples as well as most CLIP lavas have relatively flat REE patterns with $La_N/Yb_N \sim 1$ (Figure 4). REE patterns such as these can be formed from either high degrees of melting of an enriched or primitive mantle source or much lower degrees of melting from a depleted source. Low Zr/Nb (10–20), however, cannot be achieved through different degrees of partial melting, but instead requires that melts were generated from at least a partially enriched to primitive source.

[40] There are two noteworthy exceptions to the geochemical trends described above: (1) high Ba/Nb and La/Nb signatures are found in the Aruba batholith [*White et al*., 1999] and samples from NW Curaçao that could suggest a subduction influence on the magmas or magma differentiation processes and (2) high La_N/Yb_N are found in the northern portions of the CLIP including the Dumisseau Formation and <65 Ma samples from Central America [*Hoernle et al*., 2002] (Figure 6) as well as locations in South America [*Kerr et al*., 2002]. These latter compositions are more typical of ocean island basalts derived from small degrees of partial melting [*Pilet et al*., 2008].

[41] The possible subduction influence in rocks of the Aruba batholith and other evolved plutonic rocks coincides roughly with suggested collision of the CLIP with North and South America between 90 and 80 Ma [*Duncan and Hargraves*, 1984; *Pindell and Kennan*, 2009]. While some subduction signature would be expected in rocks at this time, it is perhaps most remarkable that none of the other CLIP lavas from this age and younger exhibit any such influence. It could be that any arc-derived rocks within the CLIP are underrepresented in existing studies, and/or that a newly initiated subduction zone (discussed below) would generate very limited volcanism atypical of classic subduction volcanism or adakitic signatures such as *White et al*. [1999] described in Aruba.

[42] Unlike the typical CLIP lavas found in many parts of the Caribbean region, including Curaçao, the OIB-like signature is primarily restricted to two distinct periods, 95–83 Ma lavas in the Dumisseau Formation and the <65 Ma lavas of volcanic centers in Costa Rica and Panama. The Central American samples have been described as accreted seamounts of the Galapagos hot spot trail formed in the Pacific as the Caribbean Plate was isolated from the plume with the ~70 Ma initiation of the Central American subduction zone [*Hoernle et al*., 2002]. The Haitian samples can best be explained as the result of melting beneath the northern edge of tapered plume head whose center was to the south, closer to Curaçao.

5.4. Tectonic Model

[43] Our new data show that the timing and geochemical character of the eastern CLIP exposed in Curaçao requires melting of a mantle source with a plume component over a ~30 million year period. Lower degrees of melting and a shorter volcanic history are evident in the northern extent of the CLIP. These observations do not fit a traditional plume head model for LIP development, which typically calls for a short-time span of volcanism and a rapid transition to ocean island basalt (OIB type) compositions along a spatially restricted hot spot track produced by much lower

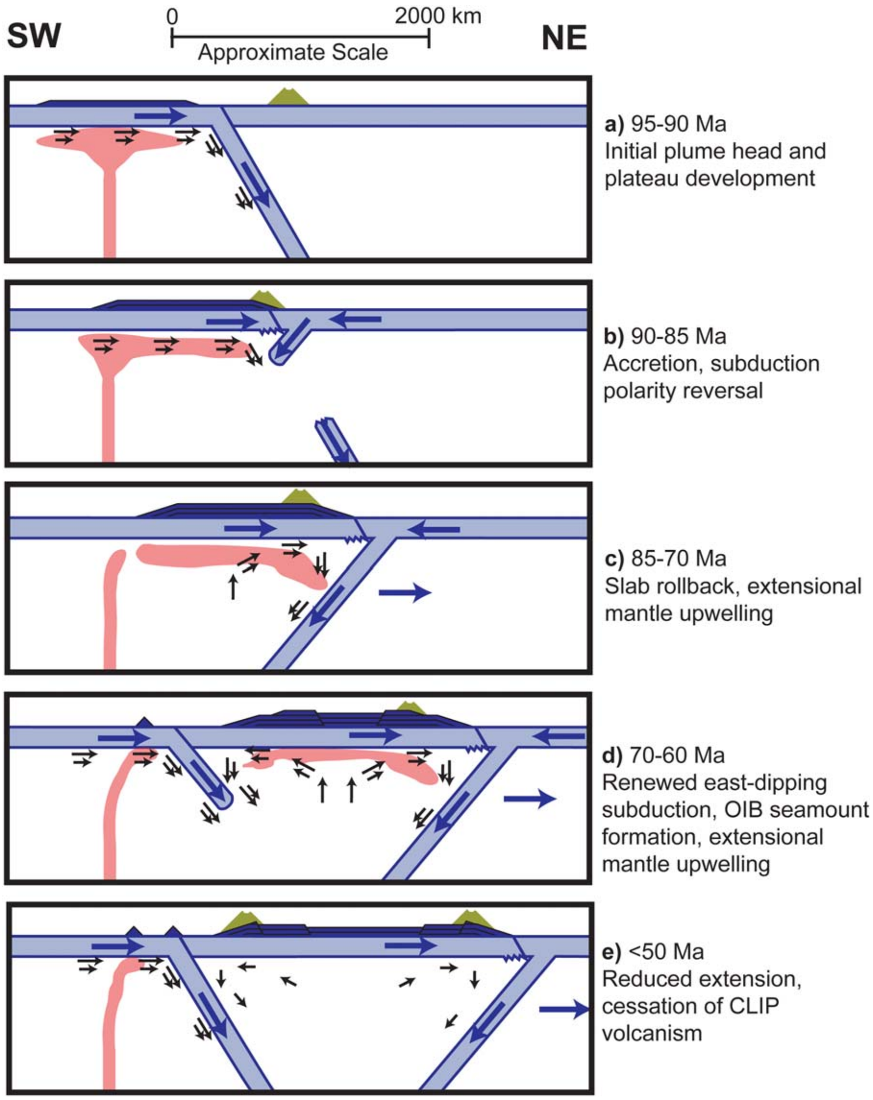

Figure 7. Conceptual model illustrating prolonged CLIP volcanism with mantle plume influence. Plume material is shown in red, oceanic lithosphere in light blue, CLIP volcanism in dark blue, and arc volcanism in green. Blue arrows depict movement of oceanic lithosphere and black arrows expected movement of asthenospheric mantle. (a) Between 95 and 90 Ma and shortly before collision between the American plates, the initial Galapagos plume head thickened the oceanic lithosphere of the Farallon plate. Unlike plume head volcanism in a fully intraplate setting, entrainment of upwelling mantle by the downgoing slab may have mixed residual plume head material diluted and extended the influence of plume-like mantle. (b) This thickened lithosphere blocked east-dipping subduction, which initiated a subduction polarity reversal between 90 and 85 Ma. During this time plateau volcanism continued and some arc activity began with initiation of a west-dipping subduction zone that continues today at the Lesser Antilles arc. (c) Slab rollback between 85 and 70 Ma dragged residual plume material to the east of the plume tail within the mantle-reference frame, as well as induced upwelling and back-arc extension allowing thinning of the plateau and continued, although less extensive, volcanism. (d and e) Initiation of east-dipping subduction after 70 Ma created the Central American volcanic arc CLIP volcanism in waned in a back-arc extensional environment while the Galapagos plume tail produced OIB seamount trails now observed in the Panama basin and in accreted seamounts in Central America.

eruption rates [*Coffin and Eldholm*, 1994; *Kerr et al.*, 2002]. Instead, we propose that the plate tectonic setting of the plateau and, specifically, the interaction of the residual plume head mantle material with nearby subduction zones, can explain the prolonged period of plume-influenced volcanism. Underlying this model is the understanding that mantle plumes can be strongly advected by ambient asthenospheric flow, particularly coupled flow at the base of the lithosphere [*Richards and Griffiths*, 1988].

[44] In our model, volcanism of the CLIP began around 94 Ma in the eastern Pacific basin during the initial impingement and decompression melting of a plume head at the base of Farallon plate oceanic lithosphere, just to the west of an east-dipping subduction zone [*Duncan and Hargraves*, 1984; Figure 7a]. At this time, we see volcanism in almost all CLIP localities (Figure 6), suggesting mantle melting was widespread and similar to other LIPs formed from plume heads [*Coffin and Eldholm*, 1994]. However, the chemical character of volcanism appears to vary with location, probably reflecting distance from the plume head center with apparently lower degrees of melting in the north of the province.

[45] Models of mantle flow beneath subduction zones show that an upwelling plume will be deflected by shear flow in the asthenosphere coupled to the base of a subducting slab [*Druken et al.*, 2012]. Applying this model to initial CLIP volcanism, the northeastward trajectory of the Farallon plate and underlying asthenosphere dragged the residual Galapagos plume head with it, thus distributing and mixing plume head material with ambient asthenosphere in a flow regime dictated by slab subduction. In this scenario, the OIB-like volcanism observed in the Dumisseau Formation was derived from the cooler, lower melt-fraction edge of the initial plume head, while the classic larger melt-fraction LIP patterns seen throughout the southern extent of the CLIP are the result of melting near the hotter main plume axis.

[46] By 85 Ma, reconstructions suggest the Caribbean Plateau collided with the Greater Antilles Arc between North and South America, blocking the existing subduction zone and causing a subduction polarity reversal [*Duncan and Hargraves*, 1984; Figure 7b]. The high La/Nb volcanism we see in Aruba and the NW edge of Curaçao, some of which has adakitic characteristics, could be the expression of the newly forming west-dipping subduction zone. After this time, the subduction zone rolled back to the east (Figure 7c). Mantle dynamic models suggest that asthenospheric counterflow will be very strong behind a rapidly rolling back slab, and eastward flow of the Caribbean region could capture the residual mantle plume and help drive continued mantle upwelling and magmatism [*Druken et al.*, 2012; *Long et al.*, 2012]. We suggest that this process entrained the residual head of the Galapagos plume, allowing for plume-like mantle to continue producing LIP volcanism for another 30 million years.

[47] Around 70 Ma east-dipping subduction began at the western margin of the CLIP, along what is now the Central American Arc (Figure 7d). This event cut off the plume tail from the Caribbean region, restricting expression of plume tail OIB volcanism to the Pacific. Evidence for this activity is found in accreted seamounts along the Central American west coast [*Hoernle et al.*, 2002; *Buchs et al.*, 2011]. This plume tail material is the result of lower degree melting resulting in observed high La_N/Yb_N seen in 66 Ma and younger samples in Central America [*Hoernle et al.*, 2002; Figure 6]. The Caribbean Plateau, now isolated from the Galapagos plume tail, experienced continued CLIP volcanism in an extensional regime between two subduction zones until ~60 Ma. During this time melting could no longer be driven by upwelling and decompression of a mantle plume, but by upwelling associated extension in a back-arc basin and the plume geochemical signature of lavas resulted from the residual plume head.

[48] The model we present here is able to explain the features observed in the CLIP although the geodynamic consequences of plume-subduction zone interactions require further study. However, the results and our interpretations from this study directly contrast some other recent work from the CLIP. *Serrano et al.* [2011] reported a similar duration of CLIP volcanism from Gorgona (98–64 Ma) as this study found for the CLF (92–62 Ma). The *Serrano et al.* [2011] study, however, called on a magmatism associated with a slab window for the Gorgona and other CLIP lavas following *Pindell et al.* [2006], with "fortuitous" coincidence of a mantle plume to explain high $^3He/^4He$ and other plume-like geochemistry in the region. As discussed in *Hastie and Kerr* [2011], the geochemistry of CLIP lavas is not compatible with a slab window environment. Also, the slab window model does not explain the focusing of volcanism in the southern Caribbean plate after 80 Ma or the clear cessation of CLIP activity by 60 Ma. In fact, we would expect a slab window initiated at 90 Ma to expand as it developed rather than contract as observed in this study.

6. Conclusions

[49] 1. We report new ^{40}Ar-^{39}Ar geochronological data and chemical data for the CLIP,

demonstrating plateau volcanism in the CLF from 92 to 63 Ma and in the Dumisseau Formation from 94 to 83 Ma. This age range significantly expands the period of formation of the CLF and reaffirms the proposed initiation of CLIP volcanism around 94 Ma.

[50] 2. Volcanism in the CLF lacks systematic geochemical changes over ~30 Ma, contradictory to a classic plume-head model where initial large degrees of voluminous melting transitions to small degree melting in only a few million years. Spatial patterns in duration and geochemical character are present over the entire CLIP with lower degrees of melting and only ~10 Ma of volcanism present along the northern margin as shown in the Dumisseau Formation.

[51] 3. All CLIP volcanism originates from a plume-like mantle source distinct from typical MORB mantle (Zr/Nb = 10–20). Most volcanism is the result of a large degree of partial melt resulting in flat REE patterns, however LREE enrichment from lower degrees of partial melt occur in the northern portion of early CLIP lavas (Dumisseau Formation, 94–83 Ma).

[52] 4. We suggest that interaction of a plume with the Greater Antilles subduction zone could explain the observed geochemistry and longevity of CLIP volcanism.

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