



HAL
open science

Late Jurassic Oceanic Crust and Upper Cretaceous Caribbean Plateau Picritic Basalts Exposed in the Duarte Igneous Complex, Hispaniola

Henriette Lapierre, Vincent Dupuis, Bernard Mercier de Lépinay, Delphine Bosch, Patrick Monié, Marc Tardy, René C. Maury, Jean Hernandez, Mireille Polvé, Delphine Yeghicheyan, et al.

► **To cite this version:**

Henriette Lapierre, Vincent Dupuis, Bernard Mercier de Lépinay, Delphine Bosch, Patrick Monié, et al.. Late Jurassic Oceanic Crust and Upper Cretaceous Caribbean Plateau Picritic Basalts Exposed in the Duarte Igneous Complex, Hispaniola. *Journal of Geology*, 1999, 107, pp.193-207. hal-03879622

HAL Id: hal-03879622

<https://hal.science/hal-03879622>

Submitted on 30 Nov 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NoDerivatives 4.0 International License

Late Jurassic Oceanic Crust and Upper Cretaceous Caribbean Plateau Picritic Basalts Exposed in the Duarte Igneous Complex, Hispaniola

Henriette Lapiere,¹ Vincent Dupuis,¹ Bernard Mercier de Lépinay,¹ Delphine Bosch,²
Patrick Monié,² Marc Tardy,³ René C. Maury,⁴ Jean Hernandez,⁵ Mireille Polvé,⁶
Delphine Yeghicheyan,⁶ and Joseph Cotten⁴

UPRES-A 5025 CNRS, Université J. Fourier, 15 rue Gignoux, 38031 Grenoble Cedex, France
(e-mail: henriette.lapiere@ujf-grenoble.fr)

ABSTRACT

Four distinct rock units have been recognized near El Aguacate, in the Janico–Juncalito–La Vega area of the Duarte complex (Dominican Republic): (1) serpentinites crosscut by numerous diabasic dikes, (2) basalts interbedded with Late Jurassic ribbon cherts, (3) picrites and ankaramites relatively enriched in incompatible trace elements, and (4) amphibolites and gneissic amphibolites chemically similar to Oceanic Plateau Basalts. Similar Ar–Ar ages of late magmatic amphibole from a picrite, and hornblende from an amphibolite (86.1 ± 1.3 Ma and 86.7 ± 1.6 Ma, respectively), suggest that the Duarte picrites are contemporaneous with the Deep Sea Drilling Program Leg 15 and Ocean Drilling Program Leg 126 basalts drilled from the Caribbean oceanic plateau. These basalts are associated with sediments containing Late Cretaceous faunas. Sr, Nd, and Pb data show that enriched picrites and amphibolites are isotopically similar to mafic lavas from previously described Caribbean plateau and Galápagos hotspot basalts. Major element, trace element, and lead isotopic features of Late Jurassic basalts and diabases are consistent with those of normal oceanic crust basalt. However, these basalts differ from typical N-MORB because they have lower ϵ_{Nd} ratios that plot within the range of Ocean Island Basalts. These rocks appear to represent remnants of the Caribbean Jurassic oceanic crust formed from an oceanic ridge possibly close to a hotspot. Later, they were tectonically juxtaposed with Late Cretaceous slices of the Caribbean-Colombian plateau.

Introduction

Oceanic plateaus represent some of the largest geological features on earth (Coffin and Eldholm 1994). Their structure and composition are still poorly understood, however, because only their uppermost levels have been drilled during Deep Sea

Drilling Program/Ocean Drilling Program (DSDP/ODP) investigations (Saunders et al. 1996). In particular, the oceanic crust on which the oceanic plateaus rest has never been studied directly, and available ages are only estimated from magnetic anomaly data. It has been suggested that most of oceanic plateaus were emplaced over young oceanic crust and, consequently, formed as a result of near-ridge hotspot activity (Floyd 1989).

The Caribbean-Colombian Oceanic Plateau (CCOP) offers a unique opportunity to study the deep levels of an oceanic plateau and the associated oceanic crust. Magmatic units considered part of this 800,000-km² structure have been drilled from the Caribbean Sea (DSDP Leg 15, Donnelly et al. 1973; ODP Leg 126, Sigurdsson et al. 1997). They consist of pillowed or massive basalt flows and shallow sills of basalt/diabase (Donnelly et al. 1973)

Manuscript received November 14, 1997; accepted November 4, 1998.

¹ UMR-6526 CNRS, Université Nice-Sophia-Antipolis, Rue A. Einstein, 06560 Valbonne, France.

² UMR 5567 CNRS, Université Montpellier II, Place E. Bataillon, 34095 Montpellier, France.

³ UPRES-A 5025 CNRS, Université de Savoie, B. P. 1104, 73011 Chambéry, France.

⁴ UMR 6538 CNRS, Université de Bretagne Occidentale, B. P. 809, 29285 Brest, France.

⁵ Université de Lausanne, BSFH 2, 1015 Lausanne, Switzerland.

⁶ UMR 5563-CNRS, Université P. Sabatier, 38 rue des Ponts, 31400 Toulouse, France.

with Late Cretaceous ages (Turonian-Campanian faunas, 93.5 ± 0.5 to 71.3 ± 0.5 Ma, according to Gradstein et al. 1994; whole-rock $^{40}\text{Ar}/^{39}\text{Ar}$, 95.7 ± 6.2 to 85.9 ± 4.5 Ma, Sinton et al. 1998). In addition, parts of the CCOP have been obducted onto the margins of both South and North America and are now exposed in southern Haiti, Curaçao, and western Colombia, where they include the depleted komatiites and enriched basalts from Gorgona (Arndt et al. 1996; Kerr et al. 1996, 1997). On the basis of new petrological and geochemical data, Lapierre et al. (1997) suggested that the enriched mafic tholeiites from the Duarte complex (Hispaniola) could be part of the CCOP.

The purpose of this article is (1) to report new ages on the picritic basalts and amphibolites of the Duarte complex that support the hypothesis of Lapierre et al. (1997) and (2) to show that the El Aguacate pillow basalts, stratigraphically interbedded with uppermost Jurassic ribbon cherts (Montgomery et al. 1994), represent remnants of the Caribbean oceanic crust, tectonically imbricated with slices of serpentized peridotites and their diabase dikes.

Geological Data

The Duarte complex consists of basaltic to ultramafic rocks metamorphosed to greenschist and amphibolite facies, intruded by subduction-related Late Cretaceous to Late Eocene plutons (Kesler et al. 1991). Bowin (1975) and Palmer (1979) proposed that this complex could represent a fragment of oceanic crust, while Draper and Lewis (1991), Lewis and Jiménez (1991), and Donnelly et al. (1990) considered it to be an ocean island or seamount.

The age of the Duarte complex remains poorly constrained. On the basis of K/Ar data from an undeformed hornblende included within a foliated tonalite (west of Piedra Blanca; fig. 1), the Duarte complex is assumed to be Early Cretaceous in age (127 ± 5 Ma; Bowin 1966). A Late Jurassic age has also been proposed for the Duarte complex because of the presence of tectonic slices of ribbon cherts exposed near the village of Aguacate (fig. 1a). These cherts yield Upper Jurassic radiolarians (Montgomery et al. 1994). Ages of undeformed hornblende tonalites that intrude the Duarte complex range between 92 and 56 Ma (Draper and Lewis 1991). Older ages, of 123–148 Ma, have been reported from gabbroic rocks belonging to the Loma de Cabrera batholith (near the Haiti–Dominican Republic frontier; Cribb et al. 1989; Draper and Lewis 1991), which intrudes the Duarte complex. However, the older ages are questionable because of the inherent

uncertainties of argon loss and argon excess with the K/Ar method.

New field data allow us to distinguish four units in the Juncalito–Janico–La Vega area (fig. 1): (1) serpentized peridotites crosscut by diabasic dikes; (2) basaltic flows stratigraphically interbedded with Upper Jurassic ribbon cherts (Montgomery et al. 1994); (3) a thick pile (≈ 1500 m) of picritic and ankaramitic basaltic flows (Lapierre et al. 1997); and, finally, (4) mafic amphibolites and amphibole-epidote gneisses tectonically overlain or underlain by the picrites/ankaramites. The contacts between these four units are faulted.

Near El Aguacate village, the Upper Jurassic basalts and sediments are thrust on the serpentized peridotites. The latter contain large orthopyroxenes that show kink band deformations. This suggests that the serpentized peridotites could represent remnants of depleted upper mantle. Pillow basalts display quenched textures, whereas massive basalts and diabases show intersertal to ophitic textures. Basalts and diabases are almost devoid of secondary minerals. Glass is partly recrystallized in smectites. Plagioclase is sometimes replaced by albite.

Picritic and ankaramitic basalts are generally strongly deformed, especially along the recent NW–SE transcurrent faults that cut out the Central Belt. This deformation develops irregular cleavages, marked by the elongation of clinopyroxene phenocrysts replaced by smectites or actinolite, and mesoscopic phacoidal fabrics in a lower greenschist facies (Draper and Lewis 1991).

However, between these high-strain corridors, picrites and ankaramites are devoid of any deformation. Igneous textures of the rocks are preserved, and local stratigraphic succession may be observed. These rocks form massive flows, < 2 m thick, interbedded with lapilli and crystal tuffs. At their base, the flows show accumulation of olivine and/or clinopyroxene crystals (picrite or ankaramite), while the tops of the flows are highly vesicular. The rocks are weakly altered and contain fresh clinopyroxene, plagioclase, and amphibole, while olivine is systematically altered in serpentine and/or chlorite.

Amphibolites and gneissic amphibolites are composed of green hornblende \pm Ca-rich plagioclase, epidote, and sphene. Preliminary geochemical data indicate that these metamorphic rocks also display enriched tholeiitic affinities with flat chondrite-normalized REE patterns very similar to those of unmetamorphosed Upper Cretaceous basalts from Curaçao and Haiti (fig. 5b; Dupuis et al. 1997).

At the southeastern extremity of the Central

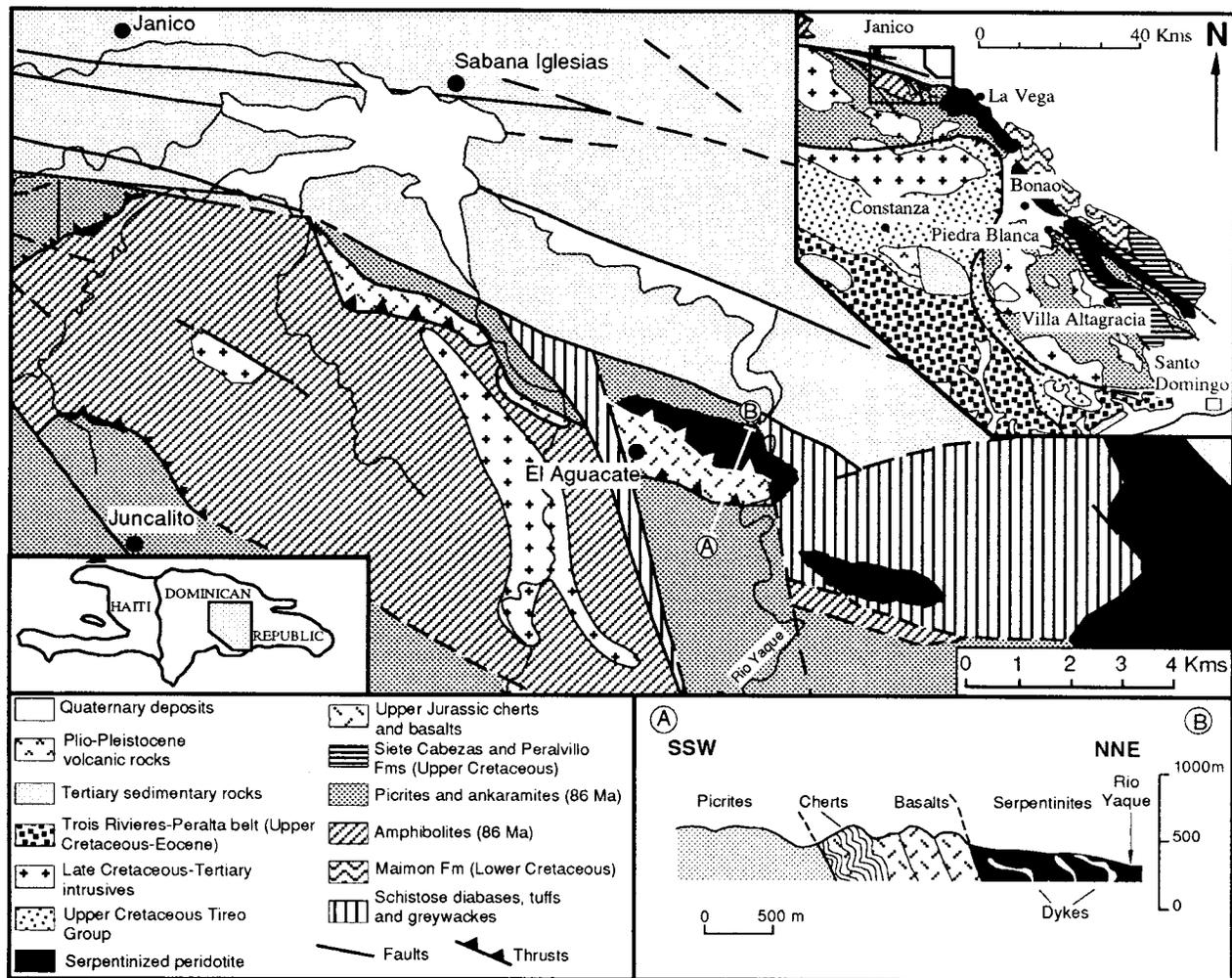


Figure 1. Geologic map of the Janico-Juncalito-LaVega area showing the four types of igneous/metamorphic units defined in the Duarte complex. *Inset at lower right*, SSW-NNE cross section of El Aguacate area showing the tectonic relationships between the Jurassic basalts and associated ribbon cherts and the serpentinized peridotite slices.

Cordillera, the amphibolites of the Duarte complex are tectonically overlain by the unmetamorphosed pillow basalts from the Siete Cabezas Formation (fig. 1). The pillow basalts of the Siete Cabezas Formation are interbedded with cherts that yield Cenomanian to Santonian radiolarians (99–83 Ma; de Wever *in* Mercier de Lépinay 1987; Donnelly et al. 1990). According to Sinton et al. (1998), though, the age of the Siete Cabezas Formation is slightly younger, i.e., Campanian to Maastrichtian (69.0 ± 0.7 and 68.5 ± 0.5 Ma; Sinton et al. 1998). The basalts of Siete Cabezas Formation show features of oceanic plateau basalts with flat chondrite-normalized REE patterns similar to those of the amphibolites (see fig. 5b; V. Dupuis, unpub. data).

Petrology and Geochemistry of the Cumulitic Picrite

A cumulitic picrite (96VD126; table 1) has been sampled along the Duarte Autopista, north of Santo Domingo ($18^{\circ}36'04''N$, $70^{\circ}08'03''W$). This rock forms, in association with other olivine and/or clinopyroxene cumulitic facies, a plug intercalated with massive Mg-rich flows and crystal tuffs. It is composed of olivine pseudomorphs, clinopyroxene rimmed by pleochroic brown magnesio-hastingsite (fig. 2), and late-crystallizing interstitial plagioclase.

Preserved clinopyroxene has a diopsidic core (Wo_{45-48} ; En_{40-45} ; Fs_{8-14}) rimmed successively by au-

Table 1. Location and Petrographic Characteristics for Upper Cretaceous Picrites and Amphibolites of the Duarte Complex, Upper Jurassic Basalts, and Diabase Dikes from Janico–La Vega–Jarabacoa

Sample	Location	Latitude	Longitude	Texture	Mineralogy	Name
96VD126	Villa Altagracia, Autopista, Santo Domingo	18°36'04"N	70°08'03"W	Cumulus-enriched	Olivine pseudomorphs, cpx, large phenocrysts rimmed by Mg-rich Hastingsite, skeletal cpx crystals, interstitial glass presently recrystallized in smectites	Picrite
96VD48	Piedra Blanca	18°51'14"N	70°20'04"W	Foliated	Tschemackitic hornblende oligoclase	Gneissic amphibolite
96VD33	Jarabacoa–La Vega; intrusive in serpentinites	19°12'55"N	70°35'12"W	Ophitic	Anhedral cpx rimmed with pale green or brown hornblende, euhedral Ca-rich plagioclase, late-crystallizing Fe-Ti oxides	Diabase
96VD35	Jarabacoa–La Vega; intrusive in serpentinites	19°12'55"N	70°35'12"W	Ophitic		Diabase
96VD39	Jarabacoa–La Vega; intrusive in serpentinites	19°13'05"N	70°35'08"W	Ophitic	Anhedral cpx rimmed with pale green or brown hornblende, euhedral Ca-rich plagioclase, late-crystallizing Fe-Ti oxides	Diabase
97VD14	El Aguacate; intrusive in serpentinites	19°13'53"N	70°40'43"W	Ophitic	Anhedral cpx rimmed by pale brown hornblende, euhedral plagioclase replaced by albite, late-crystallizing Fe-Ti oxides partly altered in titanite	Diabase
97VD07	El Aguacate; pillow basalt associated with Upper Jurassic cherts	19°14'08"N	70°41'24"W	Phyric and quenched	Olivine phenocrysts replaced by smectites, quenched cpx, abundant glassy groundmass recrystallized in smectites	Basalt
97VD08C	El Aguacate; pillow basalt associated with Upper Jurassic cherts	19°14'05"N	70°41'17"W	Intersertal	Plagioclase laths, anhedral cpx, glassy pods crystallized in smectites	Basalt
97VD09	El Aguacate; pillow basalt associated with Upper Jurassic cherts	19°13'53"N	70°41'01"W	Intersertal	Plagioclase laths, anhedral cpx, glassy pods crystallized in smectites	Basalt
97VD15	El Aguacate; massive flow associated with Upper Jurassic cherts	19°13'53"N	70°40'51"W	Aphyric	Microphenocrysts and microlites of cpx, intersertal groundmass with tiny quenched plagioclase needles	Basalt

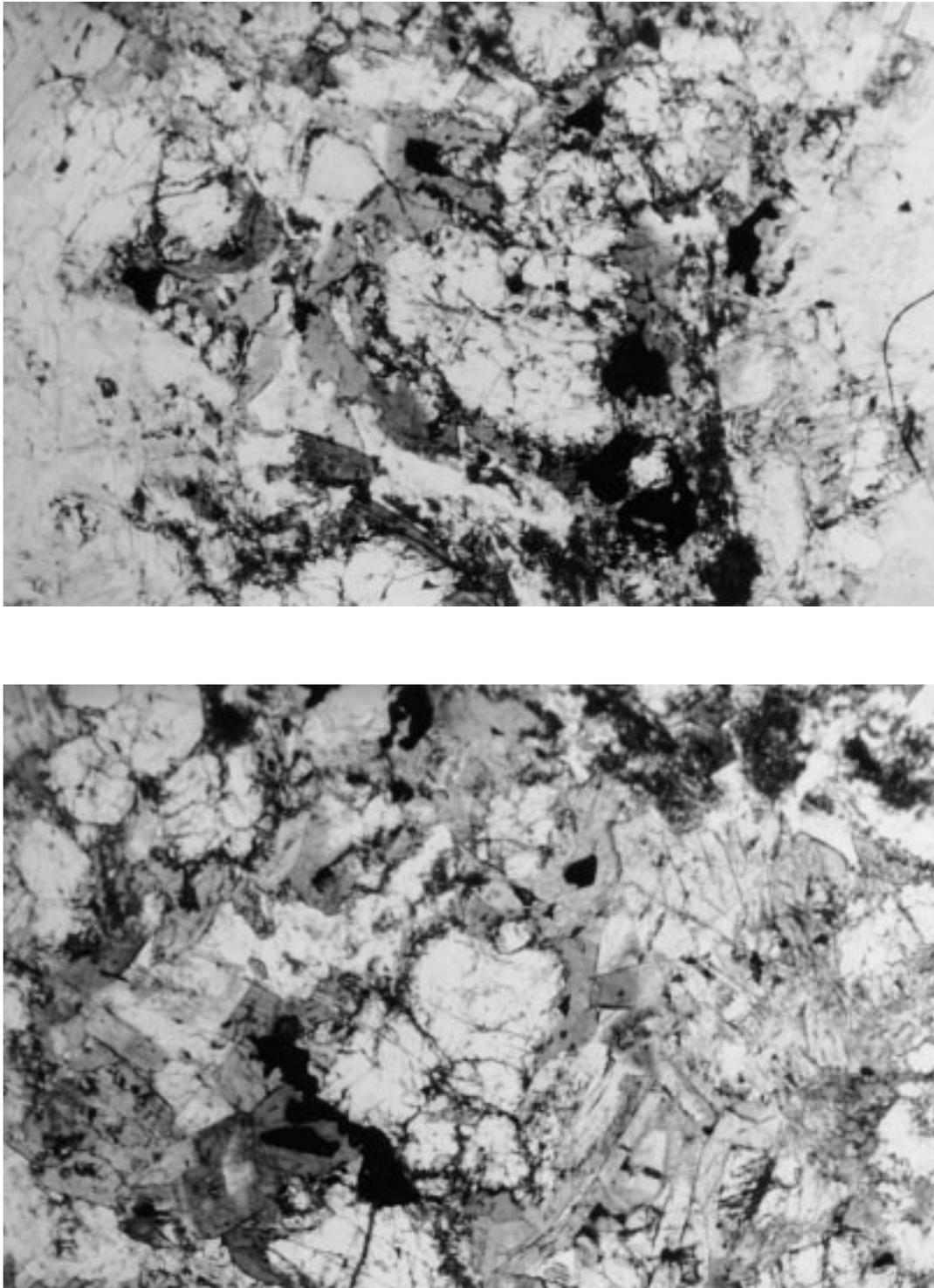


Figure 2. Microphotos of thin sections of the cumulitic picrite 96VD126 showing the clinopyroxene rimmed by the late magmatic magnesio-hastingsite.

gite (Wo_{40-43} ; En_{45-51} ; Fs_{9-12}) and Fe-rich augite (Wo_{39-42} ; En_{38-45} ; Fs_{14-23}). Locally, this clinopyroxene is rimmed by magnesio-hastingsite (fig. 3a).

Sample 96VD126 is light REE (LREE) enriched ($[\text{La}/\text{Yb}]_{\text{N}} = 4.31$; table 2; fig. 3b) relative to heavy REE (HREE) with low REE contents (around 10 times chondritic values), similar to the other Duarte picrites and ankaramites (Lewis and Jiménez 1991; Lapierre et al. 1997). Clinopyroxene (cpx) separates have moderate LREE depletion ($[\text{La}/\text{Yb}]_{\text{N}} = 0.62$), while the igneous amphibole (amph) separates have rather flat REE patterns ($[\text{La}/\text{Yb}]_{\text{N}} = 1.48$). The LREE enrichment of the whole rock with respect to cpx and amph is consistent with the preferential partitioning of REE into the melt. The host rock is more HREE depleted than cpx within it (fig. 3b). Cpx and amph separates, and their host rock, have similar ($^{87}\text{Sr}/^{86}\text{Sr}$)_i ratios ($0.70315 < [^{87}\text{Sr}/^{86}\text{Sr}]_i < 0.70320$). Moreover, the cpx and its host rock exhibit similar ϵNd ratios (+8.34 and 8.53, respectively), while that of the amphibole is slightly lower ($\epsilon\text{Nd} = 7.7$; Lapierre et al. 1999) (fig. 3c).

On the basis of the major element, trace element, and isotopic compositions of the clinopyroxene, amphibole, and host rock, we assume that (1) no metamorphic process has affected the Nd and Sr isotopic compositions of 96VD126 clinopyroxene, magnesio-hastingsite, and host rock, and (2) the magnesio-hastingsite developed during a late magmatic cooling stage of the host picrite.

$^{40}\text{Ar}/^{39}\text{Ar}$ Data

One cumulitic picrite (96VD126; table 1) and one amphibolite (96VD48; table 1) from the southern part of the Duarte complex have been dated using the $^{40}\text{Ar}/^{39}\text{Ar}$ laser probe technique of Monié et al. (1997). Step-heating experiments were performed either on a single amphibole grain (96VD48, 500 μm) or on a group of small amphiboles (96VD126, 20–50 μm) using a very defocused laser beam to ensure simultaneous degassing of all grains. The data are portrayed as age spectra and isochron plots in figure 4. Ca/K and Cl/K ratios have been estimated according to the relations: $\text{Ca}/\text{K} = 1.83(\pm 0.08) \times ^{37}\text{Ar}/^{39}\text{Ar}$, $\text{Cl}/\text{K} = 0.22(\pm 0.04) \times ^{38}\text{Ar}/^{39}\text{Ar}$ (Onstott et al. 1991).

Late magmatic amphibole 96VD126 has a flat age spectrum for a large percentage of argon released, with a corresponding plateau date of 85.4 ± 1.7 Ma (fig. 4). The isochron diagram yields an intercept age of 86.1 ± 1.3 Ma with an initial $^{40}\text{Ar}/^{36}\text{Ar}$ ratio close to the present-day atmospheric ratio. The Ca/K ratio is relatively constant for the main por-

tion of the spectrum (~ 33), with variable ratios observed in the lower temperature steps, and a higher Ca/K ratio in the last experiment. Cl/K ratios range from 0.03 to 0.06 for the main portion of the spectrum.

Calcic hornblende from amphibolite sample 96VD48 (table 1) gives an irregular age spectrum with an integrated total fusion age of 86.4 ± 2.0 Ma (fig. 4b). Approximately 65% of the gas released at high experimental temperatures yielded a plateau date of 88.6 ± 2.4 Ma, which corresponds to constant Ca/K (~ 73) and Cl/K (~ 0.03) ratios, and an isochron age of 86.7 ± 1.6 Ma. Compared to the plateau date, the age spectrum displays evidence of excess argon, then argon loss at a low experimental temperature, coupled with lower Ca/K and Cl/K ratios. These features are thought to reflect the thermal influence of the granites (fig. 1a) that intruded the Duarte complex during Late Cretaceous–Paleogene time.

Since no assumption was made on the composition of initial argon, the ages derived from the isochron plots are considered to represent the best age estimates for closure of both amphiboles. Late magmatic and metamorphic amphiboles yield statistically similar ages of 86.1 ± 1.3 and 86.7 ± 1.6 Ma, recording cooling of picrites and amphibolites at about 500°C. These dates have several possible interpretations. It could be assumed that the 86–87 Ma age records only the thermal effects of granite intrusions in the Duarte complex; however, it was demonstrated geochemically that the granite intrusion did not affect the 96VD126 cumulitic picrite. Alternatively, these dates suggest that the amphibolites and picrites cooled down simultaneously during emplacement of the Caribbean oceanic plateau over the Late Jurassic oceanic crust. This conclusion conflicts with the previously proposed Late Jurassic age for the Duarte complex based on questionable radiometric and stratigraphic age constraints.

Geochemical Results

The major element chemistry of basalts from El Aguacate and diabase dikes crosscutting serpentinites from La Vega and El Aguacate does not depart significantly from that of fresh MORB (table 2). Loss on ignition ranges from 1.8 to 4 wt %, and K_2O content remains very low. According to their MgO, Ni, and Cr contents, these rocks are mostly evolved MORBs; the only exception is sample 97VD09, which is relatively Mg-rich (9.8 wt %; table 2). Relative to enriched oceanic plateau tholeiites, these basalts are depleted in the most in-

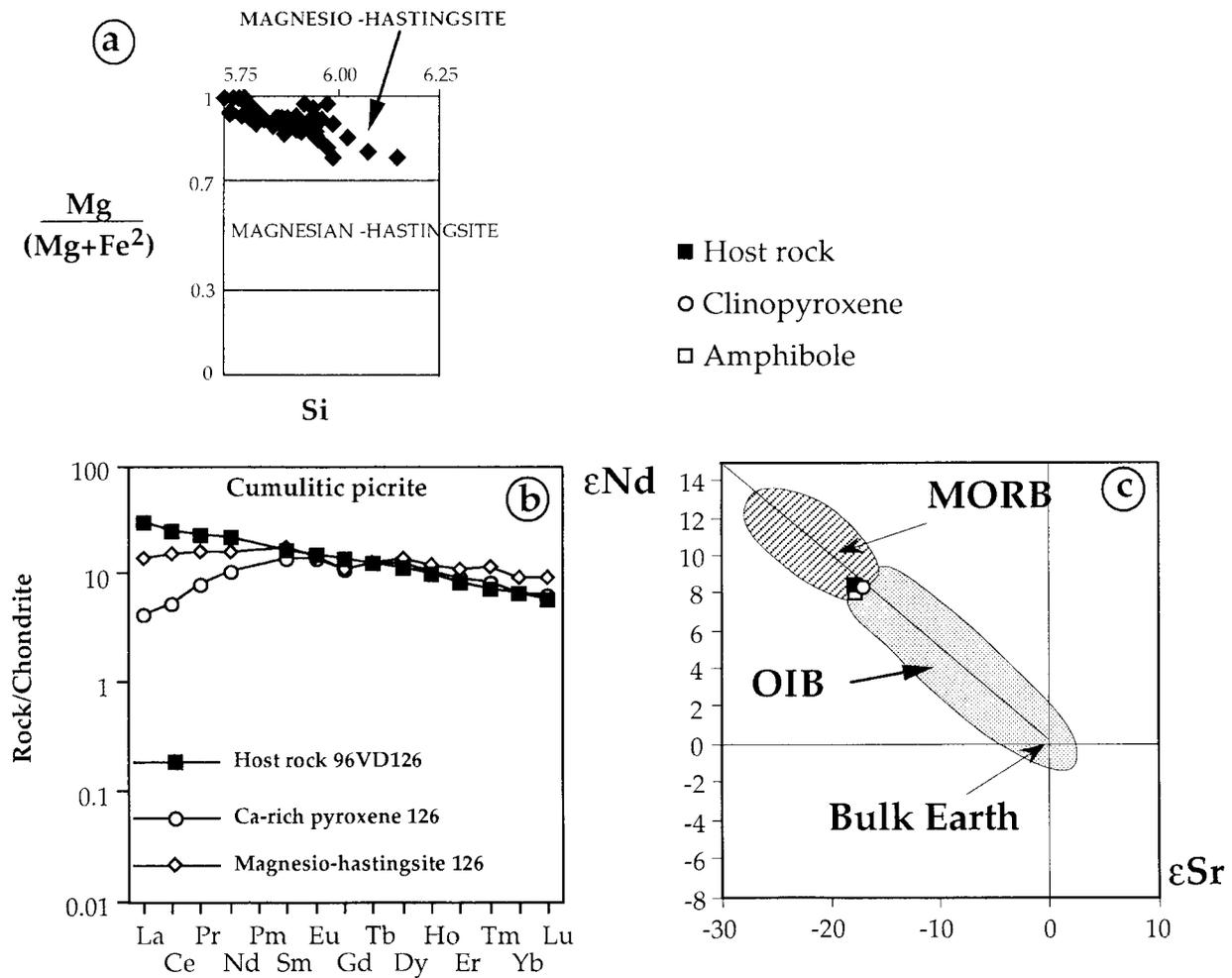


Figure 3. a, Plots of the magnesio-hastingsite in the Si versus $Mg/Mg + Fe^2$ diagram. b, Chondrite-normalized (Sun and McDonough 1989) REE patterns of the cumulitic picrite 96VD126 and host minerals (cpx and amph). c, ϵNd versus ϵSr diagram for the cumulitic picrite (96VD126) and host minerals (cpx and amph).

compatible trace elements. Despite obvious alteration effects, most of their Rb, Nb, Ta, Th, and U concentrations do not exceed those of N-MORB and are much lower than those of the Duarte enriched picrites (Lapierre et al. 1997). Corresponding REE data have been plotted in figure 5a. All the samples are LREE depleted, a characteristic typical of N-MORB but also found in some oceanic plateau basalts (Arndt et al. 1996). Again, their patterns contrast with those of Duarte picrites and ankaramites, which are consistently LREE enriched (Lapierre et al. 1997). The basalts display either slight positive or negative Eu anomalies, indicative of minor plagioclase accumulation or removal. Some basalts are more depleted than the dikes, suggesting that either they formed as a result of higher degrees

of partial melting or are derived from a more residual source than the dikes.

Initial Sr, Nd, and Pb isotopic ratios of the picrites and ankaramites of the Duarte complex have been calculated with a model age of 86 Ma. Isotopic data of diabases and basalts have been corrected for in situ decay with an age of 150 Ma on the basis of the radiolarian faunas in the ribbon cherts (table 2).

The ϵNd and ϵSr values of the diabase dikes, from Jarabacoa-La Vega and El Aguacate, range from +7.0 to +9.3 and from -18.7 to -9.8, respectively. An ϵNd - ϵSr correlation diagram (fig. 6a) shows that the initial isotopic composition of these diabases plots within or close to the field of depleted mantle, suggesting an N-MORB affinity for these rocks. The

Table 2. Major and Trace Element Contents and Sr, Nd, and Pb Isotopic Ratios of the Upper Jurassic Basalts and Diabases from Janico–Juncalito–LaVega

	Jarabacoa–La Vega			El Aguacate					
	96VD33	96VD35	96VD39	97VD14	97VD07	97VD08a	97VD08c	97VD09	97VD15
Occurrence		Dikes		Dike		Pillow			Massive flow
SiO ₂	51	51.6	50.8	52.9	50	50.5	50.2	49	51.25
TiO ₂	1.29	1.15	1.52	1.3	1.23	1.18	1.24	.83	1.33
Al ₂ O ₃	14.9	15.25	14.9	15.55	12.38	13.3	13.35	14.4	13
Fe ₂ O ₃	11.3	11.15	11.92	10.8	13.32	12.8	13.68	10.15	14.05
MnO	.16	.18	.18	.16	.19	.19	.2	.17	.19
MgO	5.13	5.8	5.45	4.52	5.23	5.2	5.75	9.18	5.7
CaO	9.45	7.7	8.6	7.45	13.5	10.85	10.2	11.7	9.46
Na ₂ O	4	4.54	3.82	5.4	1.45	1.77	1.55	1.71	2.63
K ₂ O	.04	.24	.4	.06	.03	.03	.03	.38	.13
P ₂ O ₅	.1	.06	.1	.1	.11	.1	.1	.08	.11
LOI	2.98	2.44	2.14	1.84	2.99	3.61	3.97	2.43	1.72
Total	100.35	100.11	99.83	100.08	100.43	99.53	100.27	100.03	99.57
Cr (ppm)	15	57	60	34	45	30	32	465	60
Hf	1.96	1.86	1.32	1.51	1.86	1.2	1.46	.84	2.46
Nb	.88	1.69	1.42	.94	4.25	2.4	3.23	3.41	4.47
Ni	38	37	31	30	72	57	63	186	82
Rb	.21	2.16	4.6	.45	.26	.3	.21	7.95	1.73
Sr	37.07	194.38	259.21	97	39.38	33	33	82.50	57.4
Ta	.076	.17	.14	.09	.287	.2	.23	nd	.31
Y	25.29	29.05	26	26	25.51	12	15	15.87	21.6
Zr	57.33	65.11	39.21	37	60.91	40	50	46.91	64.3
Pb	.09	1.85	.26	.13	.26	.1	.12	.282	.37
Th	.05	.11	.07	.05	.29	.1	.16	.23	.31
U	.1	.06	.02	.02	.0906	.06	.10
La	2.17	2.22	2.15	2.14	3.6	1.53	1.86	1.97	3.73
Ce	7.19	7.05	6.82	6.29	9.46	3.86	4.67	6.22	10.02
Pr	1.29	1.22	1.22	1.15	1.49	.6	.74	.96	1.59
Nd	7.2	6.36	6.17	6.2	7.64	2.89	3.58	4.96	8.03
Sm	2.64	2.49	2.42	2.23	2.62	1.04	1.28	1.55	2.67
Eu	.79	.84	.94	.84	.96	.49	.56	.58	1
Gd	3.27	2.83	2.76	2.85	3.18	1.35	1.66	2.45	3.36
Tb	.65	.68	.65	.54	.63	.28	.35	.44	.67
Dy	4.31	4.21	3.94	3.62	4.21	2.02	2.47	2.89	4.5
Ho	1.01	.93	.86	.81	.99	.47	.57	.62	1.04
Er	2.87	2.77	2.46	2.44	2.87	1.41	1.72	1.82	3.01
Tm	.43	.51	.46	.36	.44	.23	.29	.26	.46
Yb	2.86	2.82	2.51	2.43	2.85	1.6	1.94	1.8	3
Lu	.45	.42	.37	.38	.45	.26	.32	.27	.48
(La/Yb) _N	.54	.53	.58	.59	.91	.64	.65	.78	.89
²⁰⁶ Pb/ ²⁰⁴ Pb	18.197	17.127	18.094	17.964	18.497	18.255	17.929	18.161	17.413
²⁰⁷ Pb/ ²⁰⁴ Pb	15.519	15.49	15.552	15.570	15.528	15.513	15.566	15.546	15.500
²⁰⁸ Pb/ ²⁰⁴ Pb	37.747	36.803	37.781	37.857	38.316	37.818	37.605	38.058	37.829
¹⁴³ Nd/ ¹⁴⁴ Nd	.513003 ± 11	.513104 ± 6	.513155 ± 6	.513125 ± 6	.513001 ± 7	.513015 ± 6	.513012 ± 5	.51306 ± 6	.513062 ± 6
⁸⁷ Sr/ ⁸⁶ Sr	.703040 ± 15	.702739 ± 8	.703056 ± 8	.702832 ± 11	.703696 ± 11	.703669 ± 14	.703669 ± 14	.704334 ± 15	.703706 ± 30
(⁸⁷ Sr/ ⁸⁶ Sr) _i	.70301	.70267	.70295	.7028	.70365	.70361	.70363	.70363	.70350
εNd	6.89	8.33	9.31	9.04	7.76	6.88	6.93	7.52	7.04
εSr	-18.72	-27.47	-19.55	-21.58	-9.58	-10.17	-9.85	-9.83	-10.79

Note. Major and trace element data have been obtained by ICP-AES (Université de Bretagne) and ICP-MS (Université J. Fourier) using methods described by Cotten et al. (1995) and Lapiere et al. (1997), respectively. Nd and Sr isotopic compositions were determined on a Finnigan MAT261 multicollector mass spectrometer at the Laboratoire de Géochimie Isotopique de l'Université de Toulouse Refer to Lapiere et al. (1997) for the analytical technique. ²⁰⁶Pb/²⁰⁴Pb, ²⁰⁷Pb/²⁰⁴Pb, and ²⁰⁸Pb/²⁰⁴Pb isotopic ratios were measured on a multicollector VG sector mass spectrometer at the Laboratoire de Géochimie Isotopique de l'Université de Montpellier II following the analytical procedure adapted from Manhès et al. (1980). Pb total blanks are less than 65 pg.

diabase Pb/Pb isotopic ratios define a limited domain located on or close to the EPR-MORB and MAR-MORB fields, except sample 96VD35, which displays particularly depleted signatures (fig. 6*b, c*).

These rocks are characterized by low ²⁰⁶Pb/²⁰⁴Pb and ²⁰⁸Pb/²⁰⁴Pb ratios that suggest derivation from a relatively primary source similar to the Depleted MORB Mantle (DMM) reservoir. Compared to di-

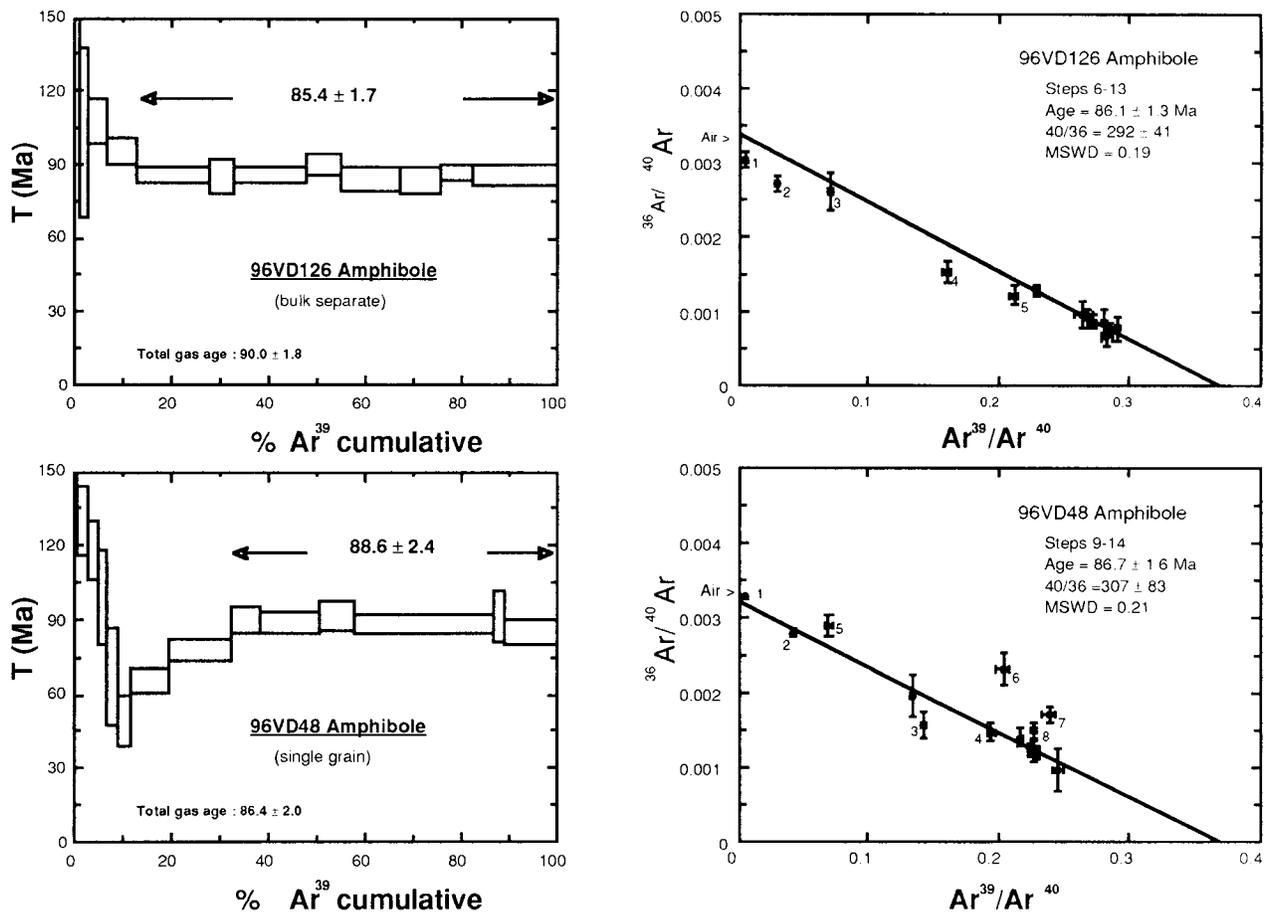


Figure 4. Ar/Ar age spectra (*left*) and isochron plots (*right*) for picrite (96VD126) and amphibolite (96VD48) samples from the Duarte complex. For the isochron plots, the labeled steps are those that have been excluded from the regression.

abase dikes, the Upper Jurassic pillow basalts from El Aguacate display lower ϵNd ranging from +6.8 to +7.7 and significantly higher ϵSr evolving from -9.6 to -10.2, likely linked to oceanic hydrothermal alteration processes. In the Nd-Sr diagram (fig. 6a), these basalts plot within a restricted field, distinct from the diabase dike domain and located within or close to the Ocean Island Basalts (OIB) field. This suggests that the El Aguacate basalts were derived from a significantly enriched source, similar to that of the 86-Ma picrites and ankaramites of the Duarte complex (Lapierre et al. 1997), and reflects the contribution of an HIMU-like enriched component. Nevertheless, on the Pb/Pb diagrams, the Pb/Pb initial isotopic ratios of the Upper Jurassic basalts (fig. 6b, c) plot close to those of the diabases (fig. 6b, c) and away from the 86-Ma picrites and ankaramites field. No indication of a noticeable contribution of an enriched component

has been detected in the Upper Jurassic basalts on the basis of Pb isotopic data.

Discussion

The chemical features, based on the trace element and Nd, Sr, and Pb isotopic compositions of the Duarte picrites/ankaramites and amphibolites, are indicative of their affinity with the previously described oceanic plateau occurrences in the CCOP, e.g., the Leg 15 and Leg 126 basalts; the Curaçao, Haiti, Gorgona, and Colombia basalts (Kerr et al. 1997); and the recent Galápagos hotspot basalts (fig. 6). The newly determined ca. 87–86 Ma ages for the picrites and amphibolites are also consistent with the Turonian-Campanian (93–71 Ma) biostratigraphic ages of Leg 15, Leg 126, and Aruba basalts, as well as with other recent Ar-Ar dates grouping around 90–87 Ma for basalts from Isla Gorgona,

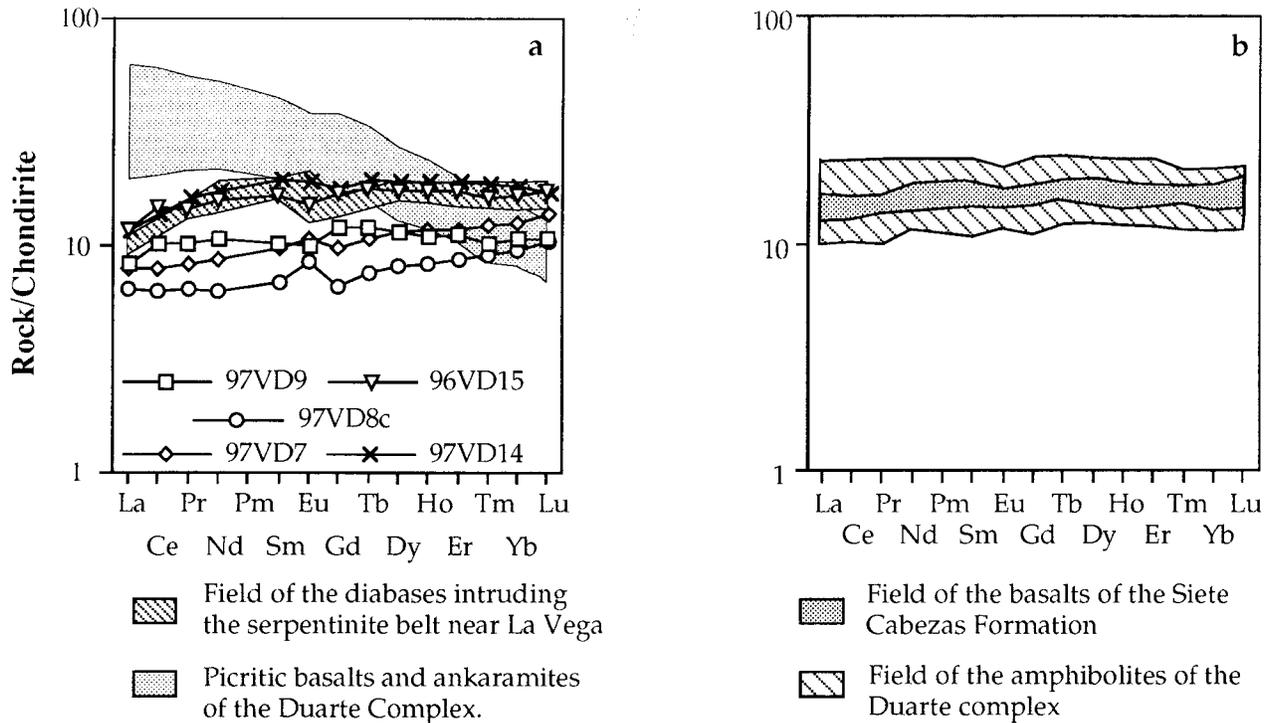


Figure 5. Chondrite-normalized (Sun and McDonough 1989) REE patterns of the Jurassic basalts and diabase dikes from El Aguacate. The fields of the picrite/ankaramite (Lapierre et al. 1997) and diabase dikes (a) of the Jarabacoa-La Vega area and the basalts of the Siete Cabezas and the amphibolites of the Duarte complex (b) (Dupuis et al. 1997; V. Dupuis, unpub. data) are shown for comparison.

Haiti, Curaçao, and the Nicoya Peninsula in Costa Rica (Alvarado et al. 1997; Sinton et al. 1997, 1998). These new ages thus confirm the occurrence of Upper Cretaceous remnants of the CCOP exposed in the Duarte complex.

The isotopic data, especially the $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{207}\text{Pb}/^{204}\text{Pb}$, $^{206}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$ initial ratios of the picrites/ankaramites and amphibolites of the Duarte complex are similar to those of the Gorgona, Curaçao, and Nicoya peninsula basalts, the LREE-enriched Dumisseau Formation basalts, and some of the young Galápagos lavas. This indicates that all these rocks were likely to have been derived from an enriched plumelike source, similar to that of the Galápagos plume.

These results allow us to constrain the geodynamic models proposed by Draper and Lewis (1991) and Draper et al. (1996) for the tectonic evolution of Hispaniola during the Cretaceous. On the basis of structural data in the Central Cordillera (Draper et al. 1996) and the presence of local unconformities and conglomerates in the Cretaceous volcanic pile from the Eastern Cordillera, Draper and Lewis (1991) and Draper et al. (1996) suggested that a col-

lision occurred at the end of the Early Cretaceous (pre-Hatillo limestone; i.e., Albian times, ~100 Ma). This collision occurred between the Duarte complex and the Early Cretaceous arc (Amina-Maimon schists, tholeiitic and calc-alkaline lavas, and arc-sediments of the Los Ranchos Formation; primitive island arc [PIA] of Donnelly and Rogers 1978, 1980; Donnelly et al. 1990; Lapierre et al. 1997). According to this model, the collision initiated a change in the subduction polarity that provoked the end of the south-facing Early Cretaceous arc growth. The subduction vergence changed from northeast to southwest, leading to the development of the Late Cretaceous arc.

Taking into account that the Duarte complex was likely formed during the early Late Cretaceous, we suggest that the collision between the Duarte complex and the Early Cretaceous arc took place after the Albian times, possibly around 86 Ma, the age of the amphibolite facies metamorphism. The latter likely developed while the uppermost levels of the oceanic plateau (the mafic amphibolites) began to subduct. Soon after, when the deepest levels of the oceanic plateau reached the trench (as they

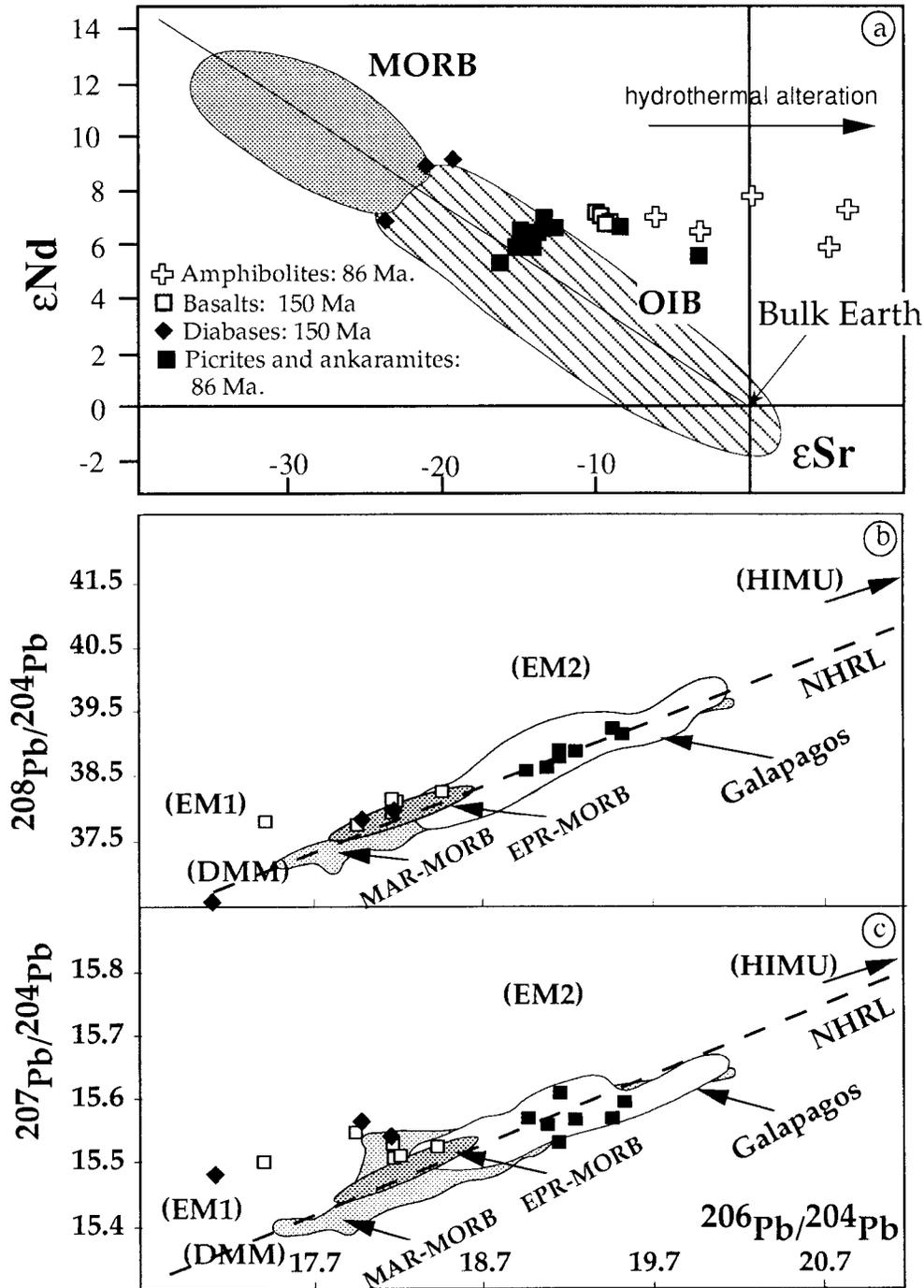


Figure 6. a, ϵNd versus ϵSr diagram for the Upper Jurassic diabases and basalts from Janico–Juncalito–LaVega area. Plots of Upper Cretaceous picrites/ankaramites and amphibolites of the Duarte complex are given for comparison. OIB and N-MORB fields are from DePaolo (1988). b, $(^{208}Pb/^{204}Pb - ^{206}Pb/^{204}Pb)_i$ correlation diagram for the Upper Jurassic diabases and basalts (this article) and Upper Cretaceous picrites/ankaramites of the Duarte complex (Lapierre et al. 1999). c, $(^{207}Pb/^{204}Pb - ^{206}Pb/^{204}Pb)_i$ correlation diagram for Upper Jurassic diabases and basalts and Upper Cretaceous picrites/ankaramites of the Duarte complex. The Galápagos lavas field and MAR and EPR-MORB domains are reported from White (1993) and White et al. (1987, 1993). The Northern Hemisphere Reference Line (NHRL) and various reservoirs (DMM, EM1, EM2, HIMU) are shown after Zindler and Hart (1986).

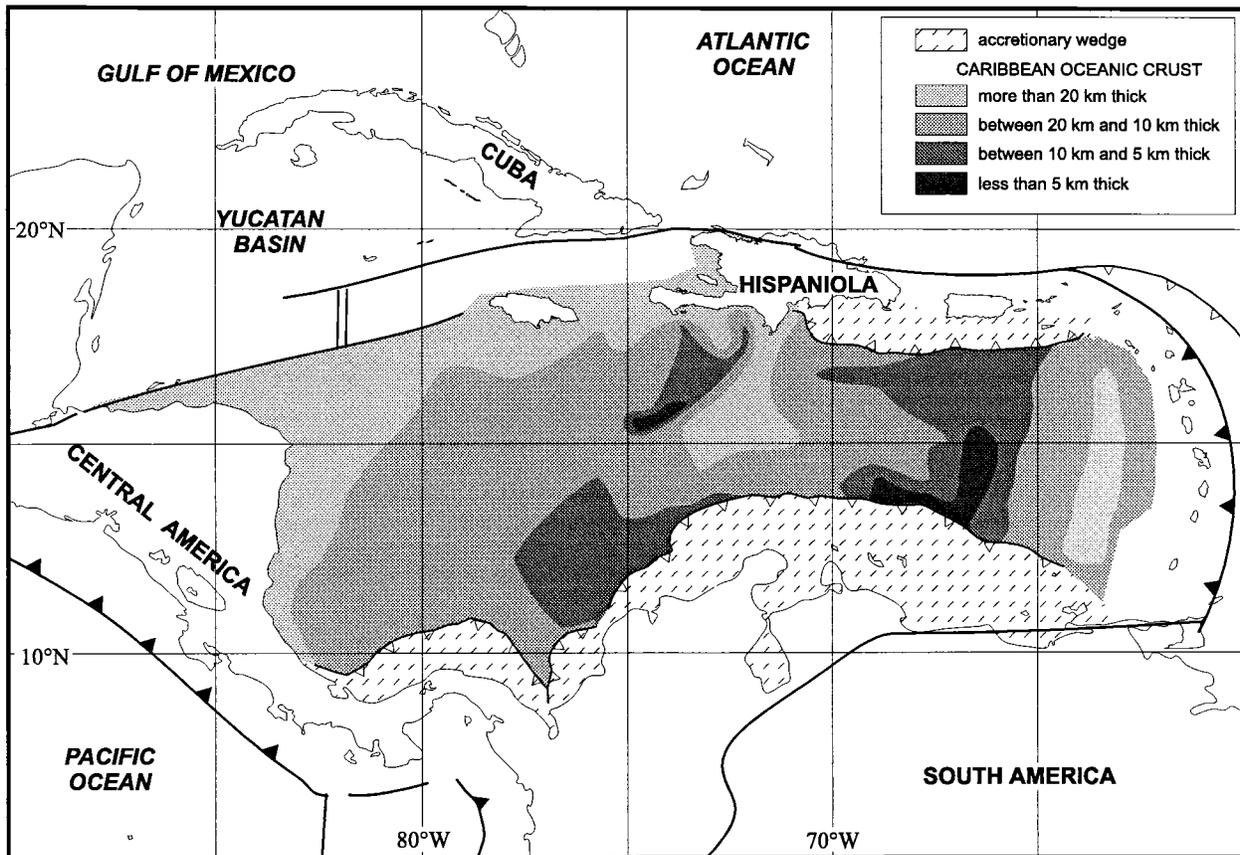


Figure 7. Map of the Caribbean oceanic floor showing the thickness variations of the Caribbean oceanic crust. The Upper Jurassic basalts and diabases could represent the remnants of the Caribbean oceanic crust whose thickness does not exceed 10 km. Data are after Houtz and Ludwig (1977), Diebold et al. (1981), Case et al. (1990), and Mauffret and Leroy (1997).

were more or less unsubductable), they blocked the subduction process; this blockage finally led to the collision of the oceanic plateau (i.e., the Duarte complex), with the Early Cretaceous arc mentioned in Draper et al. (1996).

There remains, however, the problem of the age of the Tiroo arc rocks and the structural and/or geodynamic relations of these arc rocks to the Albian collisional event. The 81.4 ± 0.8 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ age of a dacite (Lewis and Jiménez 1991) of the Tiroo Group fits with such a model. But, according to paleontological ages, the age of the Tiroo Group ranges from Cenomanian to Turonian (93–89 Ma); thus the Tiroo arc rocks are slightly older or contemporaneous with the 90–86-Ma oceanic plateau picrites and basalts. This suggests that either the oceanic plateau collided with the oldest segments (Early Cretaceous) of the arc while the youngest (Late Cretaceous) were still developing or that the arc polarity reversal occurred at the end of the Late

Cretaceous arc growth, sometime during the Late Cretaceous or Early Eocene.

The structural layout of the Duarte complex, which consists of imbricated tectonic slices of picrites/ankaramites, amphibolites, serpentinites, and Upper Jurassic basalts, could have been formed during this collisional process. During the collision, parts of thickened oceanic-plateau-like crust or unthickened normal oceanic crust were thrust on the Lower Cretaceous arc rocks, uplifted, and exhumed.

Thus, the juxtaposition of tectonic slices of the CCOP with slices of Upper Jurassic N-MORB basalts and of serpentinites containing N-MORB dikes strongly suggests that the latter could represent fragments of oceanic crust originating from the Caribbean domain. Although the Caribbean oceanic crust has never been studied in situ, there are several lines of evidence that suggest it could be at least partly Jurassic. Indeed, Jurassic ophiol-

ites have been dated from radiolarian faunas in cherts exposed in Puerto Rico and La Désirade (Montgomery et al. 1992). Remnants of Upper Jurassic oceanic crust have been described in Costa Rica, where N-MORB type basalts (Meschede et al. 1988; Meschede and Frisch 1994) are associated with Late Jurassic radiolarian cherts (Gursky 1994). Moreover, these radiolarians likely derived from the subducting Farallon plate (Mattson and Pessagno 1979; Montgomery et al. 1994).

Seismic refraction data (Mauffret and Leroy 1997) indicate that the present-day Caribbean plate crust is not uniformly thick. The thickness of the crust of the southern Venezuelan and Colombian basins and the basin south of Haiti is not greater than that of normal oceanic crust (<10 km), whereas elsewhere this thickness may reach 20 km (fig. 7). The top of the igneous basement of the thickened crust is defined seismically by a smooth reflector horizon (termed B''; Duncan and Hargraves 1984), while in the areas of normal thickness (i.e., Venezuelan and Colombian basins and basin south of Haiti), B'' reflector is topographically rougher (similar to oceanic crust) and is found at greater depths than the smooth B'' basement (Ludwig et al. 1975; Diebold et al. 1981; Bowland and Rosencrantz 1988). Rough B'' has been interpreted to be that of normal, older oceanic crust that locally, where the crust thickness reaches 20 km, was overlain by younger oceanic plateau flows and sills (smooth B'' basement). The Upper Jurassic basalts from Aguacate could represent accreted remnants of this Caribbean "normal oceanic crust" (rough B'' basement) before

they were tectonically juxtaposed with the picrites-ankaramites and amphibolites of the Duarte complex during the oceanic plateau Early Cretaceous arc collision. Indeed, these basalts do not show any high-grade metamorphism. If they represent the remnants from the overthickened Caribbean oceanic crust, over and through which the CCOP magmas were emplaced, these basalts would have experienced amphibolite and/or high-grade greenschist facies due to the overload and/or intrusion of hot plume-generated magmas.

The ϵNd ratios of the Upper Jurassic N-MORB type basalts from El Aguacate are lower than those of N-MORB and plot within the range of OIB. This feature suggests that an OIB component has been involved in the genesis of these Upper Jurassic basalts. The most likely explanation is that these basalts were originated from an oceanic ridge located near a hotspot. Indeed, it is currently suggested that most of the oceanic plateaus were formed as a result of near-ridge hotspot activity (Floyd 1989), which supports the case for the El Aguacate Upper Jurassic basalts.

ACKNOWLEDGMENTS

This work was funded by the CNRS teams UPRES-A 5025, UMR 6526, UMR 6538, UMR 5567, and UMR 5563 and has benefited from grants MENESR-DSPT3 to R. C. Maury and FNRS21-31216.91 to J. Hernandez. We thank P. Brunet (UMR 5563), who did all the Sr-Nd TIMS analyses.

REFERENCES CITED

- Alvarado, G. E.; Denyer, P.; and Sinton, C. W. 1997. The 89 Ma Tortugal komatiitic suite, Costa Rica: implications for a common geological origin in the Caribbean and eastern Pacific region from a mantle plume. *Geology* 25:439-442.
- Arndt, N. T.; Kerr, A. C.; and Tarney, J. 1996. Differentiation in plume heads: the formation of Gorgona komatiites and basalts. *Earth Planet. Sci. Lett.* 146: 289-301.
- Bowin, C. 1966. Geology of the central Dominican Republic (case history: part of an island arc). In Hess, H. H., ed. *Caribbean geological studies*. Geol. Soc. Am. Mem. 98:11-84.
- Bowin, C. O. 1975. The geology of Hispaniola. In Nairn, A. E. M., and Stehli, F. G., eds. *The Gulf of Mexico and the Caribbean (The ocean basins and margins, vol. 3)*. New York, Plenum, p. 501-552.
- Bowland, C. L., and Rosencrantz, E. 1988. Upper crustal structure of the western Colombian Basin. *Geol. Soc. Am. Bull.* 100:534-546.
- Case, J. E.; MacDonald, W. D.; and Fox, P. J. 1990. Caribbean crustal provinces: seismic and gravity evidence. In Dengo, G., and Case, J. E., eds. *The Caribbean region (Geology of North America, vol. H)*. Boulder, Colo., Geol. Soc. Am., p. 15-39.
- Coffin, M. F., and Eldholm, O. 1994. Large igneous provinces: crustal structure, dimensions and external consequences. *Rev. Geophys.* 32:1-36.
- Cotten, J.; Le Dez, A.; Bau, M.; Caroff, M.; Maury, R. C.; Dulski, P.; Fourcade, S.; Bohn, M.; and Brousse, R. 1995. Origin of anomalous rare-earth element and yttrium enrichments in subaerially exposed basalts: evidence from French Polynesia. *Chem. Geol.* 119: 115-138.
- Cribb, G. W.; Jiménez, J.; Lewis, J. F.; and Sutter, J. F. 1989. $^{40}\text{Ar}/^{39}\text{Ar}$ ages from Loma de Cabrera batholith: implications for tectonic timing of tectonic event in

- northern Hispaniola. *Geol. Soc. Am. Abstr. Prog.* 21: A-267.
- DePaolo, D. J. 1988. Neodymium isotope geochemistry (Minerals and rocks, vol. 20). Berlin, Springer, 187 p.
- Diebold, J. B.; Stoffa, P.; Buhl, P.; and Truchan, M. 1981. Venezuela Basin crustal structure. *J. Geophys. Res.* 86: 7901–7923.
- Donnelly, T. W.; Beets, D.; Carr, M.; Jackson, T.; Klaver, G.; Lewis, J.; Maury, R.; et al. 1990. History and tectonic setting of Caribbean magmatism. *In* Dengo, G., and Case, J. E., eds. *The Caribbean region (Geology of North America, vol. H)*. Boulder, Colo., *Geol. Soc. Am.*, p. 339–374.
- Donnelly, T. W.; Melson, W.; Kay, R.; and Rogers, J. J. W. 1973. Basalts and dolerites of late Cretaceous age from the central Caribbean. *Initial Rep. Deep Sea Drilling Project 15:989–1012*.
- Donnelly, T. W., and Rogers, J. J. W. 1978. The distribution of igneous rocks throughout the Caribbean. *Geol. Mijnb.* 57:151–162.
- . 1980. Igneous series in island arcs: the north-eastern Caribbean compared with worldwide island-arc assemblages. *Bull. Volcan.* 43-2:347–382.
- Draper, G.; Gutiérrez, G.; and Lewis, J. 1996. Thrust emplacement of the Hispaniola peridotite belt: orogenic expression of the mid-Cretaceous Caribbean arc polarity reversal? *Geology* 24:1143–1146.
- Draper, G., and Lewis, J. F. 1991. Metamorphic belts in central Hispaniola. *In* Mann, P.; Draper, G.; and Lewis, J. F., eds. *Geologic and tectonic development of the North America–Caribbean plateau boundary in Hispaniola*. *Geol. Soc. Am. Spec. Pap.* 262:29–45.
- Duncan, R. A., and Hargraves, R. B. 1984. Plate tectonic evolution of the Caribbean region in the mantle reference frame. *Geol. Soc. Am. Mem.* 162:81–93.
- Dupuis, V.; Lapierre, H.; Mercier de Lépinay, B.; Maury, R. C.; Tardy, M.; and Hernandez, J. 1997. Duarte complex (Hispaniola) revisited: evidence for three structural units in a remnant of the Caribbean Oceanic Plateau. *Terra Nova* 9:525.
- Floyd P. A. 1989. Geochemical features of intraplate oceanic plateau basalts. *In* Saunders, A. D., and Norry, M. J., eds. *Magmatism in the ocean basins*. *Geol. Soc. (Lond.) Spec. Publ.* 42:215–230.
- Gradstein, F. M.; Agterberg, F. P.; Ogg, J. G.; Hardenbol, J.; van Veen, P.; Thierry, J.; and Huang, Z. 1994. A Mesozoic time scale. *J. Geophys. Res.* 99: 24,051–24,074.
- Gursky, H.-J. 1994. The oldest sedimentary rocks of South Central America: the radiolarian cherts of the Nicoya Ophiolite complex (?Early Jurassic to Late Cretaceous). *In* Seyfried, H., and Hellmann, W., eds. *Geology of an evolving island arc (Profil, Bd. 7)*. Stuttgart, Universität Stuttgart, p. 265–277.
- Houtz, R. Z.; and Ludwig, W. J. 1977. Structure of the Colombia Basin, Caribbean Sea, from profiler sonobuoy measurements. *J. Geophys. Res.* 82:4861–4867.
- Kerr, A. C.; Marriner, G. F.; Arndt, N. T.; Tarney, J.; Nivia, A.; Saunders, A. D.; and Duncan, R. A. 1996. The petrogenesis of Gorgona komatiites, picrites and basalts: new field, petrographic and geochemical constraints. *Lithos* 37:245–260.
- Kerr, A. C.; Tarney, J.; Marriner, G. F.; Nivia, A.; and Saunders, A. D. 1997. The Caribbean-Colombian Cretaceous igneous province: the internal anatomy of an oceanic plateau. *In* Coffin, M. F., and Mahoney, J. J., eds. *Large igneous provinces: continental, oceanic and planetary flood volcanism (Geophys. Monogr. Ser., vol. 100)*. Washington, D.C., *Am. Geophys. Union*.
- Kesler, S. E.; Sutter, J. F.; Barton, J. M.; and Speck, R. C. 1991. Age of intrusive rocks in northern Hispaniola. *In* Mann, P.; Draper, G.; and Lewis, J. F., eds. *Geologic and tectonic development of the North America–Caribbean plateau boundary in Hispaniola*. *Geol. Soc. Am. Spec. Pap.* 262:165–172.
- Lapierre, H.; Dupuis, V.; Mercier de Lépinay, B.; Tardy, M.; Ruiz, J.; Maury, R. C.; Hernandez, J.; and Loubet, M. 1997. Is the Lower Duarte igneous complex (Hispaniola) a remnant of the Caribbean plume-generated oceanic plateau? *J. Geol.* 105:111–120.
- Lapierre H.; Dupuis, V.; Reynaud, C.; Bosch, D.; Polvé, M.; Maury, R. C.; Jean Hernandez, J.; et al. 1999. Multiple plume events in the genesis of the peri-Caribbean Cretaceous oceanic plateau. *J. Geophys. Res.*, in press.
- Lewis, J. F., and Jiménez, J. G. 1991. Duarte complex in the La Vega–Jarabacoa–Janico area, central Hispaniola: geologic and geochemical features of the sea floor during the early stages of arc evolution. *In* Mann, P.; Draper, G.; and Lewis, J. F., eds. *Geologic and tectonic development of the North America–Caribbean plateau boundary in Hispaniola*. *Geol. Soc. Am. Spec. Pap.* 262:115–141.
- Ludwig, W. J.; Houtz, R. E.; and Ewing, J. J. 1975. Profiler-sonobuoy measurements in the Colombian and Venezuela basins, Caribbean Sea. *Am. Assoc. Pet. Geol. Bull.* 59:115–123.
- Manhès, G.; Allègre, C. J.; Dupré, B.; and Hamelin, B. 1980. Lead isotope study of basic-ultrabasic layered complex: speculations about the ages of the earth and primitive mantle characteristics. *Earth Planet. Sci. Lett.* 43:370–382.
- Mattson, P. H., and Pessagno, E. A. J. 1979. Jurassic and Early Cretaceous radiolarian in Puerto Rico ophiolites: tectonic implications. *Geology* 7:440–444.
- Mauffret, A., and Leroy, S. 1997. Seismic stratigraphy and structure of the Caribbean igneous province. *Tectonophysics* 283:61–104.
- Mercier de Lépinay, B. 1987. L'évolution géologique de la bordure nord-caraïbe: l'exemple de la transversale de l'île d'Hispaniola (Grandes Antilles). Thèse d'Etat, Université Pierre et Marie Curie, no. 87–50, 336 p.
- Meschede, M., and Frisch, W. 1994. Geochemical characteristics of basaltic rocks from Central American Ophiolites. *In* Seyfried, H., and Hellmann, W., eds. *Geology of an evolving island arc (Profil, Bd. 7)*. Stuttgart, Universität Stuttgart, p. 71–85.
- Meschede, M.; Frisch, W.; and Sick, M. 1988. Interpretación geodinámica de los complejos ofiolíticos de Costa Rica. *Rev. Geol. Aér. Cent.* 63:269–277.
- Monié, P.; Caby, R.; and Arthaud, M. H. 1997. The Neo-

- proterozoic Brasiliano orogeny in northeast Brazil: $^{40}\text{Ar}/^{39}\text{Ar}$ and petro-structural data from Ceará. *Precambrian Res.* 81:241–264.
- Montgomery, H.; Pessagno, E. A.; Lewis, J. F.; and Schellkens, J. 1994. Paleogeography of Jurassic fragments in the Caribbean. *Tectonics* 13-2:725–732.
- Montgomery, H.; Pessagno, E. A.; and Munoz, I. M. 1992. Jurassic (Tithonian) radiolarians from La Désirade (Lesser Antilles): preliminary paleontological and tectonic implications. *Tectonics* 11:1426–1432.
- Onstott, T. C.; Phillips, D.; and Pringle-Goodell, L. 1991. Laser microprobe measurement of chlorine and argon zonation in biotite. *Chem. Geol.* 90:145–168.
- Palmer, H. 1979. Geology of the Moncion-Jarabacoa area, Dominican Republic, Hispaniola. *In* Lidz, B., and Nagle, F., eds. *Tectonic focal point of the northern Caribbean*. Miami, Miami Geol. Soc., p. 29–68.
- Saunders, A. D.; Tarney, J.; Kerr, A. C.; and Kent, R. W. 1996. The formation and fate of large oceanic igneous provinces. *Lithos* 37:81–95.
- Sigurdsson, H.; Leckie, R. M.; Acton, G. D.; et al. 1997. Caribbean ocean history and the Cretaceous-Tertiary boundary event. *Procedure of ODP Initial Reports*, vol. 165, 865 p.
- Sinton, C. W.; Duncan, R. A.; and Denyer, P. 1997. Nicoya Peninsula, Costa Rica: a single suite of Caribbean oceanic plateau magmas. *J. Geophys. Res.* 102: 15,507–15,520.
- Sinton, C. W.; Storey, M.; Lewis, J.; and Estrada, J. J. 1998. An oceanic flood basalt province within the Caribbean plate. *Earth Planet. Sci. Lett.* 155:221–235.
- Sun, S. S., and McDonough, W. F. 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. *In* Saunders, A. D., and Norry, M. J., eds. *Magmatism in ocean basins*. Geol. Soc. (Lond.) Spec. Publ. 42:279–292.
- White, W. M. 1993. $^{238}\text{U}/^{204}\text{Pb}$ in MORB and open system evolution of the depleted mantle. *Earth Planet. Sci. Lett.* 115:211–226.
- White, W. M.; Hofmann, A. W.; and Puchelt, H. 1987. Isotope geochemistry of Pacific mid-ocean ridge basalt. *J. Geophys. Res.* 92:4881–4893.
- White, W. M.; McBirney, A. R.; and Duncan, R. A. 1993. Petrology and geochemistry of the Galápagos Islands: portrait of a pathological mantle plume. *J. Geophys. Res.* 98:19,533–19,563.
- Zindler, A., and Hart, S. R. 1986. Chemical geodynamics. *Annu. Rev. Earth Planet. Sci.* 14:493–571.

Copyright of Journal of Geology is the property of University of Chicago Press and its content may not be copied or emailed to multiple sites or posted to a listserv without the copyright holder's express written permission. However, users may print, download, or email articles for individual use.