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Henriette Lapierre, Delphine Bosch, Vincent Dupuis, Mireille Polvé, René C. Maury, et al.. Multiple plume events in the genesis of the peri-Caribbean Cretaceous oceanic plateau province. Journal of Geophysical Research: Solid Earth, 2000, 105 (84), pp.8403-8421. 10.1029/1998JB900091 . hal-03879780

HAL Id: hal-03879780

<https://hal.science/hal-03879780>

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Multiple plume events in the genesis of the peri-Caribbean Cretaceous oceanic plateau province

Henriette Lapierre,¹ Delphine Bosch,² Vincent Dupuis,³ Mireille Polvé,⁴ René C. Maury,⁵ Jean Hernandez,⁶ Patrick Monié,² Delphine Yeghicheyan,⁴ Etienne Jaillard,¹⁻⁷ Marc Tardy,⁸ Bernard Mercier de Lépinay,³ Marc Mamberti,¹⁻⁶ Alain Desmet⁹, Francine Keller¹, and François Sénebier¹

Abstract. The oceanic crust fragments exposed in central America, in north-western South America, and in the Caribbean islands have been considered to represent accreted remnants of the Caribbean-Colombian Oceanic Plateau (CCOP). On the basis of trace element and Nd, Sr, and Pb isotopic compositions we infer that cumulate rocks, basalts, and diabbases from coastal Ecuador have a different source than the basalts from the Dominican Republic. The latter suite includes the 86 Ma basalts of the Duarte Complex which are light rare earth element (REE) -enriched and display (relative to normal mid-ocean ridge basalts, NMORB) moderate enrichments in large ion lithophile elements, together with high Nb, Ta, Pb, and low Th contents. Moreover, they exhibit a rather restricted range of Nd and Pb isotopic ratios consistent with their derivation from an ocean island-type mantle source, the composition of which includes the HIMU (high $^{238}\text{U}/^{204}\text{Pb}$) component characteristic of the Galápagos hotspot. In contrast, the 123 Ma Ecuadorian oceanic rocks have flat REE patterns and (relative to NMORB) are depleted in Zr, Hf, Th, and U. Moreover, they show a wide range of Nd and Pb isotopic ratios intermediate between those of ocean island basalts and NMORB. It is unlikely, on geochemical grounds, that the plume source of the Ecuadorian fragments was similar to that of the Galápagos. In addition, because of the NNE motion of the Farallon plate during the Early Cretaceous, the Ecuadorian oceanic plateau fragments could not have been derived from the Galápagos hotspot but were likely formed at a ridge-centered or near-ridge hotspot somewhere in the SE Pacific.

1. Introduction

Oceanic plateaus originate by the outpouring of large volumes of mafic magmas over oceanic crust coupled with cogenetic plutonic intrusions. Despite their volumetric importance, little is known about their overall structure and composition, especially of their deeper crustal levels. Because of their thickness, they tend to be more buoyant than normal oceanic crust [Burke *et al.*, 1978; Nur and Ben Abraham, 1982; Cloos, 1993; Saunders *et al.*, 1996] and are not easily subducted. Therefore these oceanic plateaus can potentially be obducted onto, or accreted to, continental margins [Ben Abraham *et al.*, 1981], thus increasing both the probability of

preservation and accessibility of their plutonic roots. Numerous accreted oceanic crustal fragments composed of ultramafic-mafic cumulate rocks, diabbases, and basalts are exposed along the Pacific coast of Central America (Costa Rica) and South America (Colombia, Ecuador) and in the Caribbean (Venezuela, Greater Antilles, Aruba, Curaçao; Figure 1). Their origin, age, and emplacement are still a matter of ongoing debate. Age estimates of these complexes range from Late Jurassic to Paleocene. They are interpreted as being parts of a large basaltic province, the Caribbean-Colombian Igneous Province [Kerr *et al.*, 1997a, b].

The Late Cretaceous Caribbean basaltic crust drilled during the Deep Sea Drilling Project (DSDP) Leg 15 [Donnelly *et al.*, 1973] and Ocean Drilling Project (ODP) Leg 165 [Sigurdsson *et al.*, 1997] is enriched in large ion lithophile elements (LILE) and has relatively radiogenic (Sr and Pb) isotopic characteristics [Sen *et al.*, 1988] which are consistent with derivation from a similar mantle source as that of the Galápagos hotspot. Since diabbases and basalts of oceanic fragments in the islands and continent bordering the Caribbean have geochemical characteristics similar to those of the drilled rocks, Donnelly *et al.* [1990] considered these rocks to represent uplifted parts of the Caribbean-Colombian Oceanic Plateau (CCOP). Using a fixed hotspot reference frame, Duncan and Hargraves [1984] suggested that the CCOP was produced during the initial "plume head" phase of the Galápagos hotspot.

The CCOP is mostly made of Upper Cretaceous diabbases, shallow basaltic sills, or pillowed and/or massive flows of

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Paper number 1998JB900091.
0148-0227/00/1998JB900091\$09.00

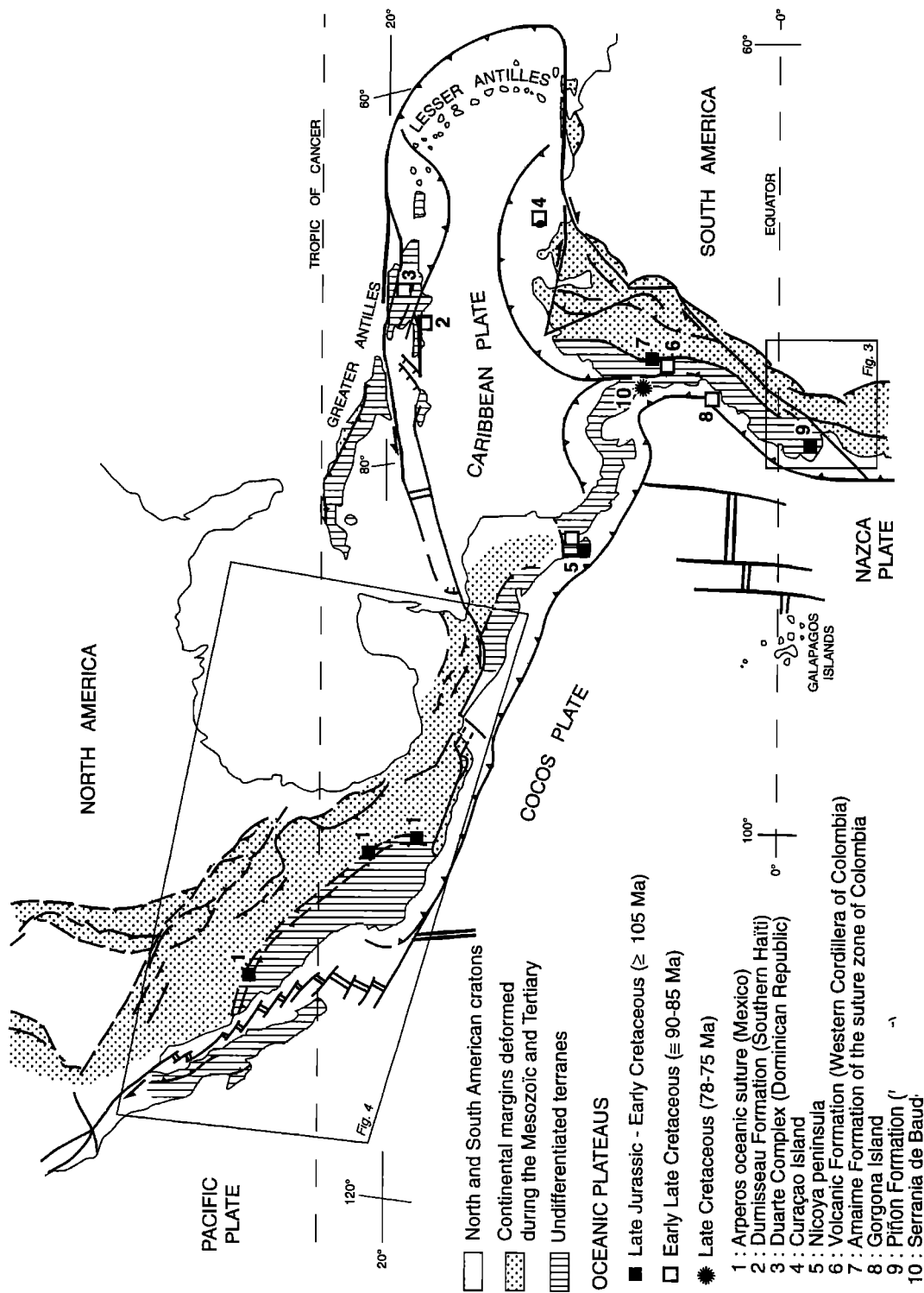


Fig. 4 Schematic map showing the location of the Mesozoic oceanic plateau crustal fragments exposed in Mexico, Costa Rica, Greater Antilles, Curaçao, Aruba, Colombia, and western Ecuador.

basalts, the latter being often picritic [Donnelly *et al.*, 1973]. Exposures of these lavas are reported in southern Haiti, Curaçao, and western Colombia (including the komatiites and enriched basalts from Gorgona Island) [Aitken and Echeverria, 1984; Arndt *et al.*, 1996; Kerr *et al.*, 1996a, 1997a]. Kerr *et al.* [1996a, b, c, 1997a] demonstrated that the enriched tholeiites (including komatiites) from Gorgona, Curaçao, and Colombia (with the exception of the Central Cordillera [Kerr *et al.*, 1997a]) are Upper Cretaceous in age (73–91.7 Ma) and likely derived from the Galápagos hotspot. Recent Ar/Ar ages and Sr, Nd, and Pb isotopic data indicate that the enriched basalts of the Nicoya Complex from Costa Rica, now considered to be the westernmost occurrence of the CCOP, are early Late Cretaceous in age (88–92 Ma) and can also be genetically linked to the Galápagos plume [Alvarado *et al.*, 1997; Hauff *et al.*, 1997; Sinton *et al.*, 1997]. Recently, Sinton *et al.* [1998] demonstrated on the basis of $^{39}\text{Ar}/^{40}\text{Ar}$ ages that the igneous rocks of the CCOP were emplaced during two main events: 90–82 Ma and 78–68 Ma. The rocks related to the early Late Cretaceous event (90–83 Ma, specifically Turonian to Santonian) were produced by a hotspot that possibly was the Galápagos, while those emplaced during the Late Cretaceous (78–68 Ma) possibly derived from a more depleted plume source.

Exposures of mafic plutonic and volcanic rocks with enriched tholeiitic affinities exposed in western Ecuador (Piñón Formation, see Figures 1 and 3) (C. Reynaud *et al.*, Oceanic plateau and island arcs of southwestern Ecuador: Their place in the geodynamic evolution of northwestern America, submitted to *Tectonophysics*, 1998, herein after referred to as Reynaud *et al.*, submitted manuscript, 1998) have also been assigned to the CCOP [Kerr *et al.*, 1996b, 1997a]. However, these rocks are older than those from most of the CCOP, since they are locally overlain by early Late Cretaceous (\approx 95–90 Ma) sediments [Jaillard *et al.*, 1995; Reynaud *et al.*, submitted manuscript, 1998]. Furthermore, in the Central Cordillera of Colombia, part of the accreted fragments of an oceanic plateau were affected by Early Cretaceous high-pressure metamorphism (K/Ar ages [Toussaint and Restrepo, 1994]) and are older than 120 Ma. Finally, the enriched tholeiites of the Arperos basin exposed in central and western Mexico (Figure 1) [Freydier *et al.*, 1996], are geochemically similar to those of western Ecuador (see below). Moreover, they share with the rocks of western Ecuador similar Early Cretaceous age because they are stratigraphically interbedded with cherts that yielded Lower Cretaceous radiolarian faunas [Dávila Alcocer and Martínez Reyes, 1987].

There is presently some geochemical data (age, major, trace element, and Nd, Sr, and Pb isotopic compositions) on oceanic plateau basalts, for example, the Ontong Java plateau basalts exposed in the Solomon Islands [Tejada *et al.*, 1996] and the Upper Cretaceous komatiitic and picritic basalts from the Caribbean and northern South America. However, most of these exposures are still restricted to the volcanic levels of oceanic plateau crust, and none of them allows investigation to be made of the geochemical features of the underlying ultramafic and mafic plutonic roots of the oceanic plateau. The oceanic crustal fragments from Hispaniola and more specifically from Ecuador offer the unique opportunity to study different components of the CCOP, i.e., the Upper Jurassic oceanic crust basement and the Cretaceous ultramafic and mafic hypabyssal and volcanic rocks and their plutonic roots.

Major and trace element compositions and isotopic data, although necessary, cannot identify the parental hotspot(s) of these oceanic plateau magmas. Ages and transport directions of the allochthonous oceanic crustal fragments together with kinematics of regional plates are also required to constrain parental hotspot location.

The purpose of the present paper is to report new data on the trace element and isotopic (Sr, Nd, Pb) characteristics of selected clinopyroxene- and/or olivine-rich basalts of the Duarte Complex (Dominican Republic) and plutonic and volcanic rocks from coastal Ecuador. From the comparison of these data with our published data on basalts and diabases from westerncentral Mexico and those already available in the literature, we propose a new interpretation of the origin of the Caribbean-Colombian Oceanic Plateau.

2. Geological Information

2.1. Dominican Republic

The Duarte Complex forms the core of the Central Cordillera of the Dominican Republic. It is bounded on both sides by arc-derived rocks of Cretaceous age and intruded by Late Cretaceous to Tertiary plutons (Figure 2) [Kesler *et al.*, 1977]. Bowin [1975] and Palmer [1979] proposed that this complex represents a fragment of oceanic crust. Draper and Lewis [1991] and Lewis and Jiménez [1991] consider this complex to be a Late Jurassic–Early Cretaceous ocean island or seamount modified by Late Cretaceous–Eocene island arc magmatism [Bowin, 1966; Kesler *et al.* 1977; Mercier de Lépinay, 1987; Draper and Lewis, 1991]. Donnelly *et al.* [1990 p. 347] consider the picrites, ankaramites, and amphibolites of the Duarte Complex and the Upper Cretaceous unmetamorphosed mafic rocks of the Siete Cabezas to represent the "tectonized allochthon of the Caribbean Cretaceous basaltic rocks."

Detailed field mapping in the Juncalito-Janico-La Vega area allowed us to distinguish four units in the Duarte Complex (Figure 2), the first three of which are particularly important geochemically in the context of the present study: (1) a thick pile of Mg-rich basalts, (2) mafic amphibolites and amphibole-epidote gneisses tectonically imbricated with the Mg-rich basalts, (3) pillowed and massive basalts stratigraphically associated with Upper Jurassic (160–149 Ma) ribbon cherts [Montgomery *et al.*, 1994], and (4) serpentinized peridotites crosscut by diabase dikes.

The olivine and clinopyroxene (cpx)-rich basalts are metamorphosed to greenschist facies and are generally intensively deformed. However, the stratigraphic bedding marked by the flow contacts and the graded bedding in the pyroclastic levels are locally preserved, and the plagioclase-free, Mg-rich lavas form massive flows, < 2 m thick, interbedded with lapilli and crystal tuffs. These flows show evidence for accumulation of olivine and clinopyroxene crystals at their base, while their tops are highly vesicular. They are often intruded by diabase dikes. In the southeastern extremity of the Central Cordillera (Figure 2) the amphibolites of the Duarte Complex are tectonically overlain by the unmetamorphosed diabases, basalts, and cherts of the Siete Cabezas Formation containing Cenomanian to Santonian (97–83 Ma [Gradstein *et al.*, 1994]) radiolarians [Mercier de Lépinay, 1987; Donnelly *et al.*, 1990].

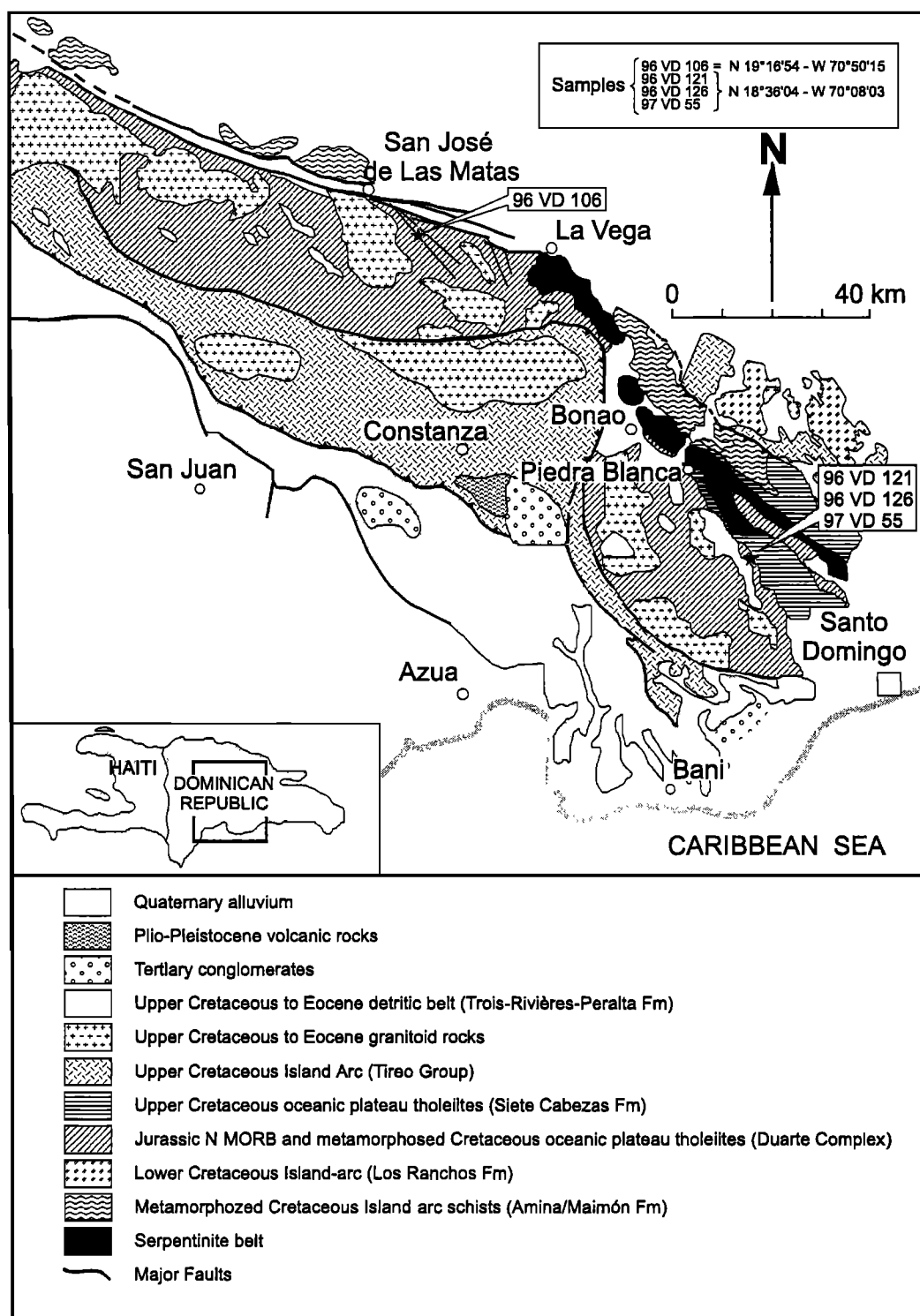


Figure 2. Schematic map of the Duarte Complex in the Central Belt from Dominican Republic showing the location of the analyzed samples discussed in the text.

Ar/Ar ages of 86 ± 1.4 Ma of both late magmatic amphibole (magnesian-hastingsite) from a cumulus-enriched rock and of hornblende from an amphibolite (96VD126, see below) [Lapierre *et al.*, 1999] indicate that the Mg-rich lavas and amphibolites of the Duarte Complex are contemporaneous with the oceanic plateau tholeiites of the CCOP exposed in the Caribbean and Central America.

2.2. Ecuador

Three main geological domains can be distinguished (Figure 3). The NNE trending Andean Cordillera is predominantly composed of deformed Paleozoic to Mesozoic metamorphic rocks [Aspden and Litherland, 1992; Noble *et al.*, 1997] crosscut and overlain by the products of Tertiary magmatic

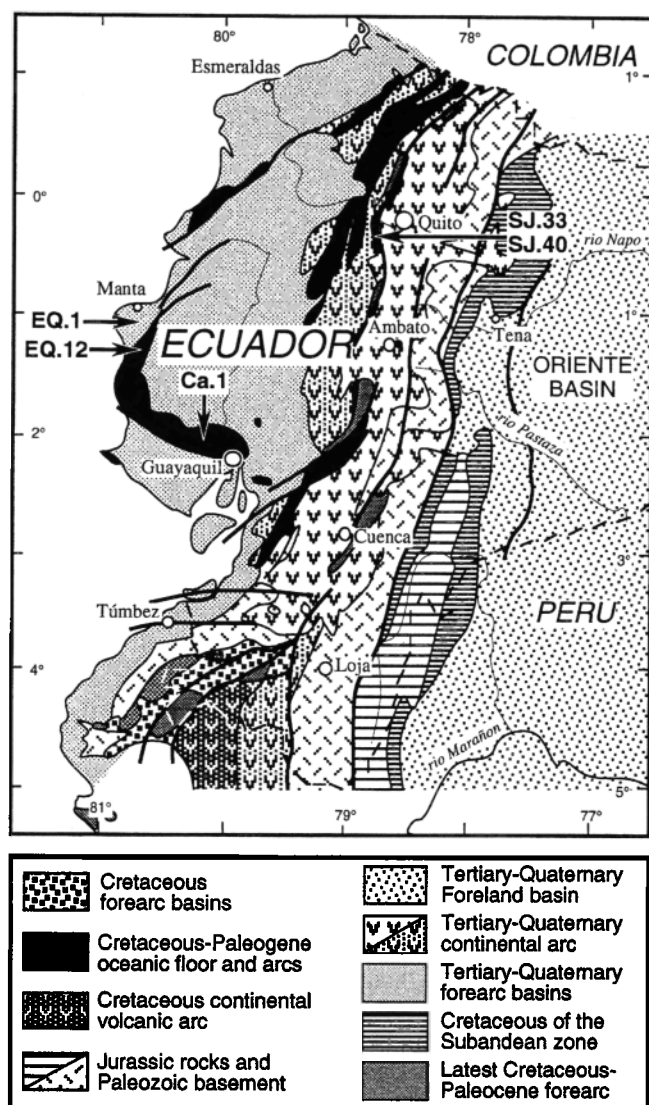


Figure 3. Schematic map of Ecuador showing the location of the analyzed samples discussed in the text.

arcs [Aspden *et al.*, 1992; Lavenu *et al.*, 1992]. Cretaceous to Paleogene continental volcanic arcs cropping out in southwestern Ecuador represent the continuation of the magmatic arc of Peru [Jaillard *et al.*, 1996].

The western coastal zone comprises an oceanic igneous basement, unconformably overlain by early Late Cretaceous to Paleogene intraoceanic arcs [Lebrat *et al.*, 1987; Bourgois *et al.*, 1990; R. Marksteiner and A. Alemán, unpublished report, 1991], in turn, overlain by Tertiary forearc marine sediments. The igneous basement (i.e., the Piñón Formation) consists of pillow basalts and diabases which yielded dubious K/Ar ages on plagioclase and whole rocks ranging from 110 to 54 Ma [Goossens and Rose, 1973]. This basement is stratigraphically overlain by undated volcanic rocks of oceanic arc origin, which are in turn overlain by pelagic sediments containing Cenomanian(?) to Turonian faunas. Thus the age of the oceanic basement of Coastal Ecuador can be regarded as pre-early Late Cretaceous.

In the eastern part of the coastal zone (i.e., the Western Cordillera) the Cretaceous-Paleogene magmatic rocks are in

fault contact with the basement of the Andean Cordillera. Tectonic slices of ophiolitic series pinched along this contact were interpreted as remnants of an oceanic crust [Juteau *et al.*, 1977; Lebrat *et al.*, 1987] or an oceanic plateau [Desmet, 1994]. The island arcs and their oceanic basement were accreted to the margin of the South American Plate during Late Cretaceous to late Paleocene times [Jaillard *et al.*, 1996; Cosma *et al.*, 1998]. In summary, coastal Ecuador is a fragment of oceanic lithosphere of pre-Late Cretaceous age (> 91 Ma), overlain by early Late Cretaceous to Tertiary intraoceanic volcanic arc series.

2.3. Western Central Mexico

The Guerrero volcano-plutonic arc was accreted to the continental margin of western Mexico before Cenomanian times [Tardy *et al.*, 1986]. It is presently separated from the Precambrian and Paleozoic terranes of Mexico by the Arperos oceanic suture (Figure 4). In northwestern and central Mexico the Arperos suture contains scattered outcrops of submarine mafic lava flows and diabases overlain by pelagic sediments containing Early Cretaceous radiolarian fauna [Dávila Alcocer and Martínez Reyes, 1986].

3. Analytical Procedures

Diabases, and cpx- and/or olivine-rich basalts experienced hydrothermal alteration and metamorphism up to the greenschist facies. Accordingly, only those samples with well-preserved original igneous mineralogy (i.e., clinopyroxene, amphibole, and plagioclase phenocrysts) and devoid of any significant petrographic alteration features were selected for study. Phenocrysts were separated then purified by hand picking. The petrographic features of these rocks are summarized in Table 1. However, actinolite rims around some cpx crystals could not be completely removed.

For Sr and Nd isotopic analyses, mineral separates and host rock powders were leached in a 2 N HCl-0.1 N HF mixture. For Pb isotope determinations, mineral separates and whole rocks were successively leached in hot 2 N HCl for 20 min in an ultrasonic bath, rinsed with tridistilled water, leached in cold 1 N HNO₃ for 20 min, and rinsed with tridistilled water in an ultrasonic bath for 15 min.

Trace elements were analyzed by inductively coupled plasma mass spectrometry (ICP-MS) at the University of Grenoble after acid dissolution. Rare earth element (REE) were first separated as a group and spiked with pure Tm using procedures described by Barrat *et al.* [1996]. Standards used for the analyses were JB2, WSE BIR-1, JR1, and UBN (Table 2). Major element analyses were performed by ICP-optical emission spectroscopy at the Université de Bretagne Occidentale. Major and trace element analyses of the minerals and host rocks are presented in Table 2.

The ¹⁴³Nd/¹⁴⁴Nd and ⁸⁷Sr/⁸⁶Sr isotopic characteristics were determined on a Finnigan MAT261 multicollector mass spectrometer at the Laboratoire de Géochimie de l'Université Paul Sabatier (Table 3), using the analytical procedures of Lapierre *et al.* [1997]. The 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 (Table 3)

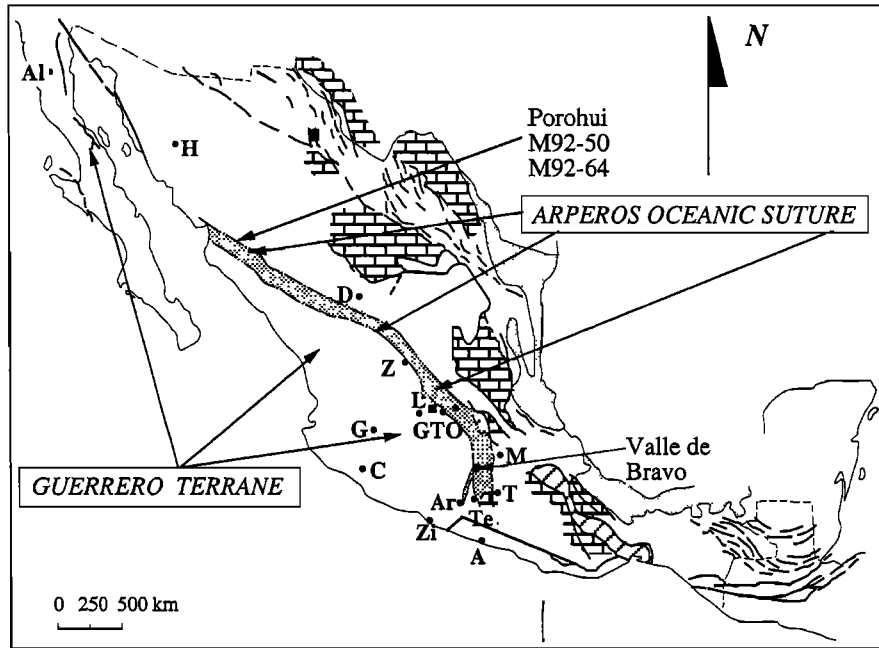


Figure 4. Schematic map of the Arperos basin and the Guerrero terrane showing the location of the samples quoted in the text. A, Acapulco; Al, Alisitos; Ar, Arcelia; C, Colima; D, Durango; G, Guadalajara; GTO, Guanajuato; H, Hermosillo; L, Leon; M, Mexico city; T, Taxco; Te, Teloloapan; Z, Zacatecas; Zi, Zijuatanejo.

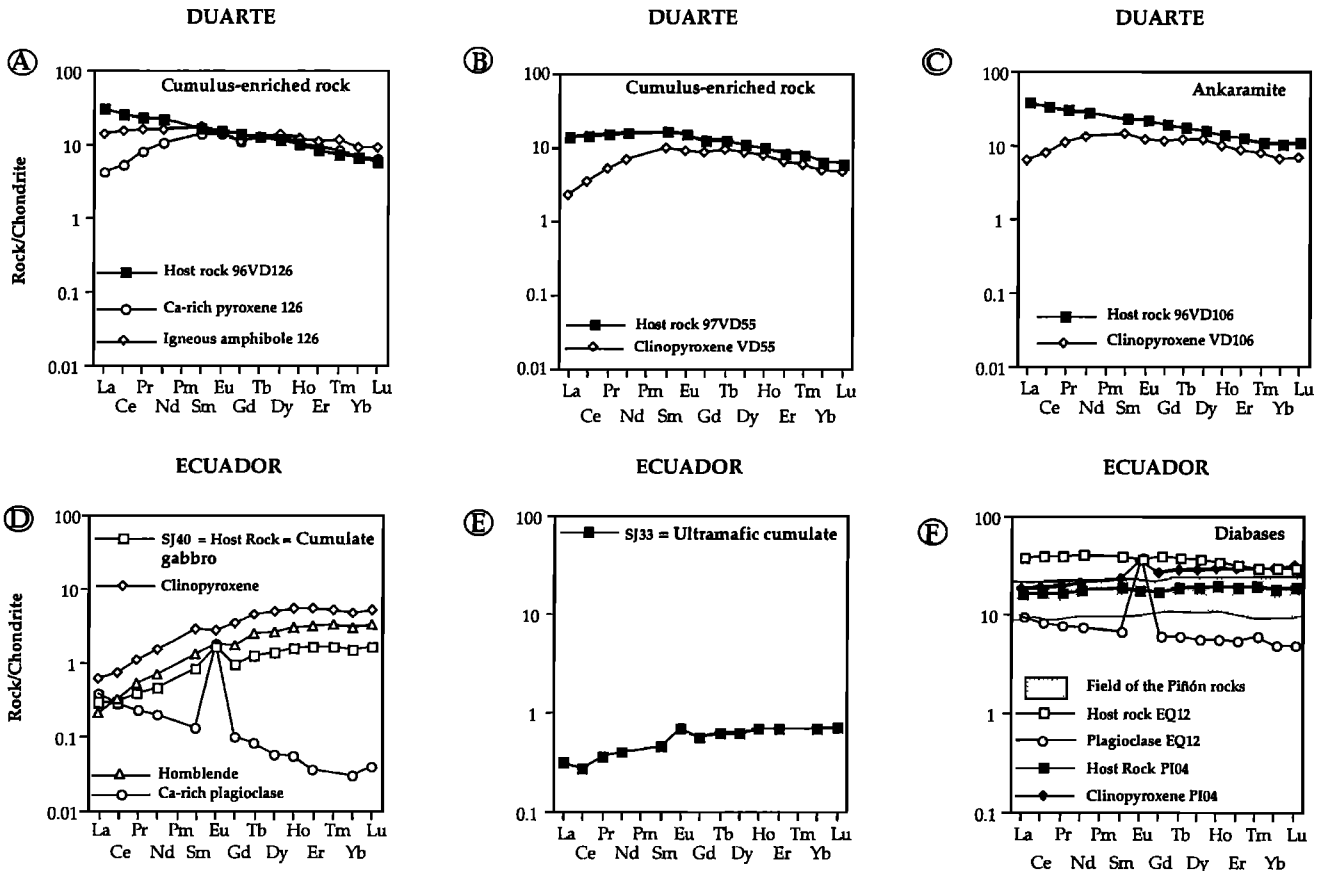


Figure 5. Chondrite-normalized (N) rare earth element patterns of the minerals and host rocks which show oceanic plateau affinities. San Juan cumulates and Piñón diabases are from Ecuador. Cumulus-enriched picrites and ankaramites belong to the Duarte Complex from Dominican Republic. Chondrite values are from Sun and McDonough [1989].

Sample	
96VD126	96VD121
Duarte Complex	Villa Altagracia
Autopista Santo Domingo	Autopista Santo Domingo
cumulus-enriched	cumulus-enriched
olivine pseudomorphs (5%)	cpx large crystals (90%)
large cpx phenocrysts (80%)	interstitial glass (10%) present,
rimmed by Mg-rich Hastingsite (3%)	recrystallized to smectites
skeletal cpx crystals	
interstitial glass (12%) present	
recrystallized to smectites	
cpx-rich cumulative basalt	cpx-rich cumulative basalt
South Janico road to Juancalito	Villa Altagracia Autopista Santo Domingo
porphyritic	porphyritic
cpx large crystals (30%) in a quenched groundmass (70%) with skeletal cpx	cpx large crystals (60%) rimmed locally by actinolitic hornblende
microclites	glassy groundmass (40%)
gabbro	
epidote + chlorite (10%)	
diabase	
Sample	Sample
97VD55	EQ12
96VD106	PJO4
North of Guayaquil	Puerto Cayo
interstitial	ophitic
plagioclase laths (50%)	plagioclase laths (50%)
cpx (40%)	interstitial cpx (40%)
epidote + chlorite (10%)	Fe-Ti oxides (10%)
diabase	diabase
Sample	Sample
M92-64	M92-50
Porohui	Porohui
interstitial	interstitial
plagioclase (40%) laths and microclites	plagioclase (40%) laths and phenocrysts replaced to albite
cpx (20%)	small cpx crystals (20%)
calcite-filled vesicles (20%)	groundmass (40%)
groundmass (40%)	basalt
basalt	basalt
Sample	Sample
M93-17	M92-50
Valle de Bravo	Porohui
porphyritic	interstitial
skeletal olivine (5%) replaced to calcite + Crspinel	plagioclase (40%) laths and phenocrysts replaced to albite
quenched Ti-rich cpx (15%)	small cpx crystals (20%)
oxides (5%) in the groundmass (75%)	groundmass (40%)
basalt	basalt
Sample	Sample
M93-17	M92-50
Valle de Bravo	Porohui
porphyritic	interstitial
skeletal olivine (5%) replaced to calcite + Crspinel	plagioclase (40%) laths and phenocrysts replaced to albite
quenched Ti-rich cpx (15%)	small cpx crystals (20%)
oxides (5%) in the groundmass (75%)	groundmass (40%)
basalt	basalt
Sample	Sample
M93-17	M92-50
Valle de Bravo	Porohui
porphyritic	interstitial
skeletal olivine (5%) replaced to calcite + Crspinel	plagioclase (40%) laths and phenocrysts replaced to albite
quenched Ti-rich cpx (15%)	small cpx crystals (20%)
oxides (5%) in the groundmass (75%)	groundmass (40%)
basalt	basalt
Sample	Sample
M93-17	M92-50
Valle de Bravo	Porohui
porphyritic	interstitial
skeletal olivine (5%) replaced to calcite + Crspinel	plagioclase (40%) laths and phenocrysts replaced to albite
quenched Ti-rich cpx (15%)	small cpx crystals (20%)
oxides (5%) in the groundmass (75%)	groundmass (40%)
basalt	basalt
Sample	Sample
M93-17	M92-50
Valle de Bravo	Porohui
porphyritic	interstitial
skeletal olivine (5%) replaced to calcite + Crspinel	plagioclase (40%) laths and phenocrysts replaced to albite
quenched Ti-rich cpx (15%)	small cpx crystals (20%)
oxides (5%) in the groundmass (75%)	groundmass (40%)
basalt	basalt
Sample	Sample
M93-17	M92-50
Valle de Bravo	Porohui
porphyritic	interstitial
skeletal olivine (5%) replaced to calcite + Crspinel	plagioclase (40%) laths and phenocrysts replaced to albite
quenched Ti-rich cpx (15%)	small cpx crystals (20%)
oxides (5%) in the groundmass (75%)	groundmass (40%)
basalt	basalt
Sample	Sample
M93-17	M92-50
Valle de Bravo	Porohui
porphyritic	interstitial
skeletal olivine (5%) replaced to calcite + Crspinel	plagioclase (40%) laths and phenocrysts replaced to albite
quenched Ti-rich cpx (15%)	small cpx crystals (20%)
oxides (5%) in the groundmass (75%)	groundmass (40%)
basalt	basalt
Sample	Sample
M93-17	M92-50
Valle de Bravo	Porohui
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oxides (5%) in the groundmass (75%)	groundmass (40%)
basalt	basalt
Sample	Sample
M93-17	M92-50
Valle de Bravo	Porohui
porphyritic	interstitial
skeletal olivine (5%) replaced to calcite + Crspinel	plagioclase (40%) laths and phenocrysts replaced to albite
quenched Ti-rich cpx (15%)	small cpx crystals (20%)
oxides (5%) in the groundmass (75%)	groundmass (40%)
basalt	basalt
Sample	Sample
M93-17	M92-50
Valle de Bravo	Porohui
porphyritic	interstitial
skeletal olivine (5%) replaced to calcite + Crspinel	plagioclase (40%) laths and phenocrysts replaced to albite
quenched Ti-rich cpx (15%)	small cpx crystals (20%)
oxides (5%) in the groundmass (75%)	groundmass (40%)
basalt	basalt
Sample	Sample
M93-17	M92-50
Valle de Bravo	Porohui
porphyritic	interstitial
skeletal olivine (5%) replaced to calcite + Crspinel	plagioclase (40%) laths and phenocrysts replaced to albite
quenched Ti-rich cpx (15%)	small cpx crystals (20%)
oxides (5%) in the groundmass (75%)	groundmass (40%)
basalt	basalt
Sample	Sample
M93-17	M92-50
Valle de Bravo	Porohui
porphyritic	interstitial
skeletal olivine (5%) replaced to calcite + Crspinel	plagioclase (40%) laths and phenocrysts replaced to albite
quenched Ti-rich cpx (15%)	small cpx crystals (20%)
oxides (5%) in the groundmass (75%)	groundmass (40%)
basalt	basalt

[illegible]

Locations, samples, and rock types are given Limits of detection Zr = 24 ppb, Nb = 5 ppb, Ta = 0.5 ppb, Hf = 1 ppb, U, Th and Pb = 0.6 ppb

*Analytical conditions of microprobe analysis 15 kV, 10–20 nA, focused beam, natural standards

Major elements reported on volatile free basis after Desmet [1994] and Reynaud et al. [submitted manuscript 1988] not analyzed but below detection limit

#Zoned any mean analysis is without summification

#Zoned cpx, mean analysis is without signification Microprobe analyses of major elements are available on request

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Table 3. Nd, Sr, and Pb Isotopic Analyses for the Duarte Complex, Ecuadorian, and Mexican Minerals and Host Rocks

Facies	($^{206}\text{Pb}/^{204}\text{Pb}$) _i	($^{207}\text{Pb}/^{204}\text{Pb}$) _i	($^{208}\text{Pb}/^{204}\text{Pb}$) _i	$^{143}\text{Nd}/^{144}\text{Nd}$	$^{87}\text{Sr}/^{86}\text{Sr}$	($^{87}\text{Sr}/^{86}\text{Sr}$) _i	εNd	εSr	
Cumulate	19.094	15.550	38.603	0.513051 ± 4	0.703190 ± 6	0.70315	+8.53	-17.77	Duarte
96VD126									
Amphib. 126	19.158	15.601	38.956	0.513054 ± 6	0.703163 ± 18	0.70315	+7.99	-17.77	85 Ma
Cpx - 126				0.513100 ± 6	0.703233 ± 13	0.70320	+8.34	-16.98	Hispaniola
Ankaramite	19.537	15.588	39.188	0.512951 ± 4	0.703520 ± 8	0.70349	+6.45	-12.87	
96VD106									
Cpx 106	19.252	15.557	38.941	0.512957 ± 7	0.703642 ± 12	0.70362	+5.52	-11.06	
Cumulate	19.146	15.525	38.800	0.512936 ± 8	0.703867 ± 25	0.70370	+6.19	-9.95	
96VD121									
Amphib. 121	19.466	15.563	39.267						
Cumulate	18.966	15.565	38.621	0.512979 ± 9	0.703234 ± 8	0.70318	+6.57	-17.34	
97VD55									
Cpx 55	18.712	15.563	38.168	0.513073 ± 7	0.703270 ± 18	0.70321	+7.56	-16.89	Appetos
Pillow basalt				0.512997 ± 36	0.704372 ± 11	0.70432	+7.2	-0.72	
M92-50	18.271	15.570	37.948	0.513027 ± 13	0.704435 ± 11	0.70432	+8.2	-0.70	110 Ma
M93-17									
Pillow basalt	18.304	15.558	38.099	0.512912 ± 48	0.704720 ± 8	0.70455	+5.8	+2.49	Mexico
M92-64									
Diabase	17.898	15.595	37.825	0.513008 ± 6	0.703506 ± 11	0.70348	+6.98	-12.43	Pifion
PiO4									
Cpx PiO4	17.414	15.548	37.166	0.513043 ± 6	0.703588 ± 10	0.70358	+7.53	-11.06	123 Ma
Diabase EQ12				0.513026 ± 6	0.703561 ± 12	0.70349	+7.69	-12.27	Ecuador
Plagio. EQ12				0.512055 ± 30	0.703327 ± 21				
Diabase EQ1	18.159	15.529	37.840	0.513154 ± 25	0.703451 ± 27	0.70321	+10.1	-16.24	
Diabase CA1	18.923	15.566	38.431	0.512870 ± 7	0.704542 ± 17	0.70435	+4.49	-0.03	
Gabbro SJ40	18.193	15.602	38.100						
Plagio. SJ40	18.126	15.473	37.890	0.512822 ± 18	0.703162 ± 7	0.70316	+4.62	-17.01	
Cpx. SJ40				0.513079 ± 11	0.703588 ± 10	0.70348	+5.84	-12.44	
Amphib. SJ40				0.513046 ± 16	0.703473 ± 20	0.70335	+5.59	-14.33	
Ultramafic SJ33				0.512822 ± 14	0.703448 ± 13	0.70282	+3.17	-13.10	

Pb isotope ratios were corrected with a mass discrimination factor of 0.13% per atomic mass unit relative to values of the NBS-981 standard measured during this period: $^{206}\text{Pb}/^{204}\text{Pb} = 16.936 \pm 0.006$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.494 \pm 0.006$ and $^{208}\text{Pb}/^{204}\text{Pb} = 36.721 \pm 0.013$. Pb isotope ratios 2σ uncertainties are assumed to be less than 0.15%.

Table 4. Sm and Nd Contents and $^{143}\text{Nd}/^{144}\text{Nd}$ Ratios From SJ13 Whole Rock, Amphibole, and Plagioclase Concentrates

Sample	Nd, ppm	Sm, ppm	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$
SJ13 whole rock	8.40	2.68	0.193	0.513008 ± 29
SJ13 plagioclase	0.99	0.18	0.108	0.512962 ± 08
SJ13 amphibole	27.59	9.63	0.211	0.513045 ± 04

The Sm and Nd concentrations have been determined by isotope dilution using a mixed ^{149}Sm and ^{146}Nd enriched solution. Sm/Nd errors are 1%

following the analytical procedure adapted from *Manhès et al.* [1980]. Total Pb blanks are less than 65 pg for a 100 mg sample.

Isotopic data on minerals and host rocks have been corrected for in situ decay with an age of 86 Ma (Dominican Republic samples) and 123 Ma (Ecuador samples). This is based on Ar/Ar ages measured on Duarte igneous amphiboles [Lapierre et al., 1999] and on a Sm/Nd internal isochron age determined on a gabbro from Ecuador, respectively (Table 4).

4. Trace Element Chemistry on Mineral Separates and Their Host Rocks

4.1. Dominican Republic

REE patterns of samples 96VD126 (olivine and cpx-rich basalt) and 96VD106 (cpx-rich basalt) are light REE (LREE)-enriched ($3.4 < (\text{La}/\text{Yb})_N < 4.3$; Table 2 and Figure 5) with low REE contents (around 10 times chondritic values). These data are in agreement with previous works [Kerr et al., 1996b, 1997a]. Sample 97VD55 (cpx cumulate) differs from the others, being less enriched in LREE ($(\text{La}/\text{Yb})_N = 2.04$). Clinopyroxenes have very similar REE_N patterns with moderate LREE depletions ($0.45 < (\text{La}/\text{Yb})_N < 0.95$), whatever their host rock type. Amphiboles have rather flat REE patterns ($(\text{La}/\text{Yb})_N = 1.48$). The LREE enrichment of whole rock with respect to clinopyroxene (cpx) and amphibole (amph) is consistent with the preferential partitioning of REE into the melt. The heavy REE (HREE) levels in the host rock and cpx are quite similar, with the exception of 96VD126 host rock which is more HREE-depleted than its cpx (Figure 5a).

Relative to normal mid-ocean ridge basalts (NMORB) (Figure 6), these rocks and their minerals show moderate enrichment in LILE and high Nb, Ta, and Pb contents. Their Th/U ratios ($3.34 < \text{Th}/\text{U} < 6.75$; Figure 7) fall within the range of the mid-Cretaceous tholeiites from Costa Rica [Hauff et al., 1997; Sinton et al., 1997]. In the cumulus-enriched rocks, trace element patterns of minerals and related host rocks are more or less parallel. This is not the case for the cpx-rich basalt where the host rock is markedly enriched in Th, Ta, and Nb with respect to the cpx. Pb has similar behavior in the cpx and in its host rock. This suggests that Nb, Ta, and Pb were concentrated in the groundmass.

The Duarte Mg-rich rocks show a wide range of Nb/U and Pb/Ce ratios (Figure 7) ($29.9 < \text{Nb}/\text{U} < 96.6$; $0.01 < \text{Pb}/\text{Ce} < 0.09$) but with U contents significantly lower than those of ocean island basalts (OIB) ($0.96 < \text{U} < 1.68$). Th/U is higher and Nb/Ta and Zr/Hf are generally lower than NMORB (Figure 7).

4.2. Ecuador

The diabases of the Piñon Formation (Reynaud et al., submitted manuscript, 1998) differ from the Duarte cpx-rich basalt in having flat REE patterns ($0.87 < (\text{La}/\text{Yb})_N < 1.28$; Table 2 and Figure 5). Compared to the host rock, PIO4 cpx has similar REE abundances but differs in the degree of LREE depletion ($(\text{La}/\text{Yb})_N = 0.61$) and is enriched in HREE. The EQ12 Ca-rich plagioclase REE concentrations are significantly lower than those of its host rock, and this mineral is LREE-enriched compared to the HREE ($(\text{La}/\text{Yb})_N = 1.94$; Table 2 and Figure 5).

The cumulate rocks from western Ecuador (SJ33, SJ40; Table 1) and SJ40 cpx differ from the Duarte cumulus-enriched rocks (96VD126, 97VD55) and related cpx in having significantly lower REE contents (Table 2; < 10 times the chondritic abundances) and a marked LREE depletion (Figure 5). The whole rock SJ40 and its related cpx and hornblende have similar parallel REE patterns, characterized by a significant LREE depletion ($0.06 < (\text{La}/\text{Yb})_N < 0.19$; Figure 5 and Table 2). The cpx and its host rock have the highest and lowest REE levels, respectively, which are < 10 times the chondritic values. Hornblende has lower La and Ce abundances than the host rock. Ca-rich plagioclase is LREE-enriched ($(\text{La}/\text{Yb})_N = 11.57$; Table 2). Finally, the cumulate wehrlite is LREE-depleted ($(\text{La}/\text{Yb})_N = 0.45$) and has negative Ce ($\text{Ce}/\text{Ce}^* = 0.51$) and positive Eu ($\text{Eu}/\text{Eu}^* = 1.24$) anomalies.

Relative to NMORB, the Piñon diabases have high Nb, Ta, and Th values, characteristic of plume-generated magmas. Moreover, their Th/U ratios are slightly higher than those of NMORB (Table 2 and Figure 6) with the exception of EQ12. However, these rocks differ from the Duarte cumulus-enriched olivine and/or cpx-rich basalts by their lower contents of Zr, Hf, U, Th, Nb, and Ta ($38.14 < \text{Nb}/\text{U} < 52$; Table 2 and Figures 6 and 7). The Pb/Ce ratios of these rocks are low ($0.008 < \text{Pb}/\text{Ce} < 0.07$) with the exception of the cumulate gabbro ($\text{Pb}/\text{Ce} = 3.45$) but generally higher than those of MORB.

4.3. Western Mexico

The Arperos basalts presented here belong to group 1 [Freydier et al., 1996]. They differ from the Piñon rocks by a greater LREE enrichment relative to HREE ($(\text{La}/\text{Yb})_N \sim 2$; Table 2 and Figure 8) which is nevertheless smaller than that of the Duarte cpx-rich basalts.

Relative to NMORB, the Arperos basalts are enriched in Th, U, Ta, and Nb but slightly depleted in Hf and Zr. Their U, Th, Hf, and Zr abundances are higher than those of the Piñon rocks and more or less similar to those of the Duarte cpx-rich basalts (Figure 6). In contrast, their Nb and Ta contents are intermediate between those of Piñon and Duarte rocks. Their Nb/U ratios (12.33 to 33.5) are lower than those of the Duarte and Piñon rocks (Figure 7). Their Pb/Ce ratios are low (0.045 and 0.062) but slightly higher than those of the Piñon rocks.

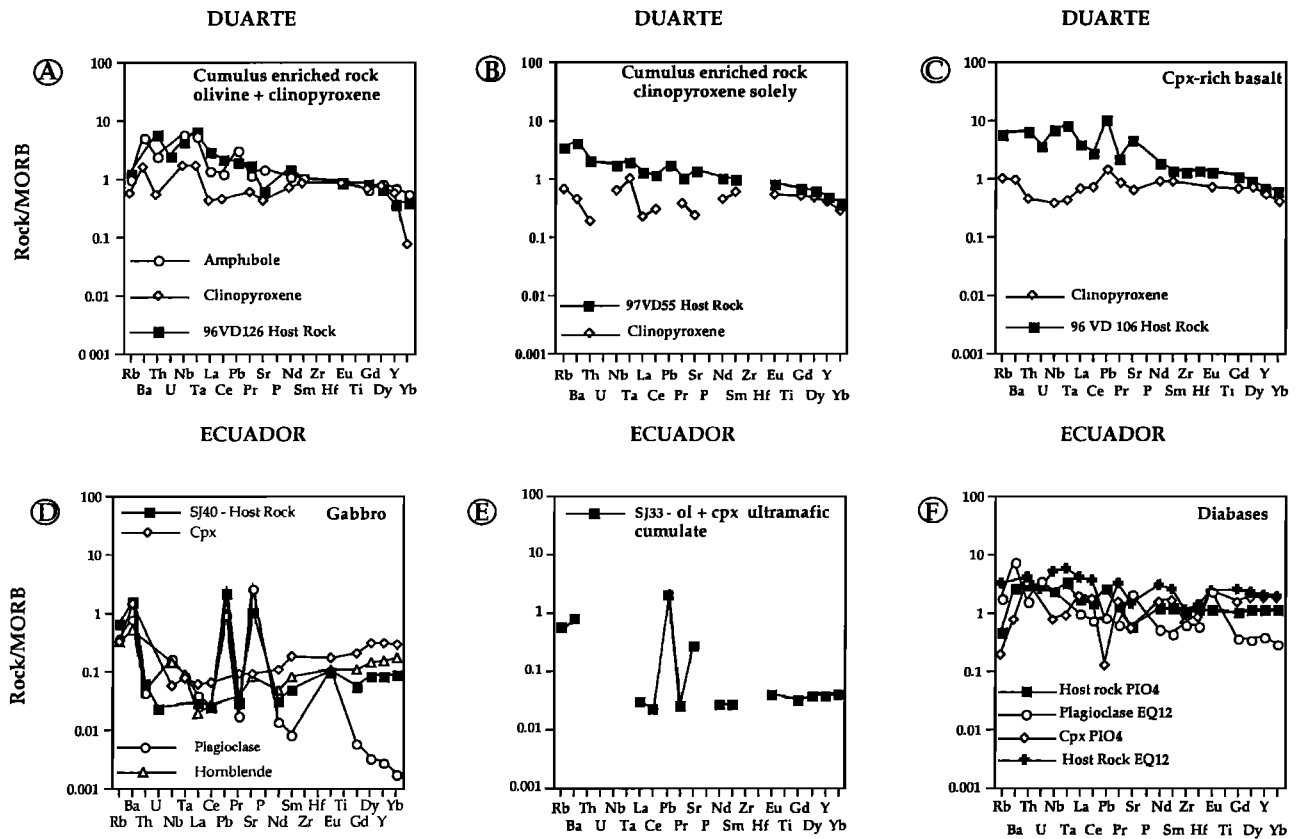


Figure 6. NMORB-normalized trace element patterns for the minerals and host rocks from Dominican Republic and Ecuador. NMORB values are from *Sun and McDonough* [1989].

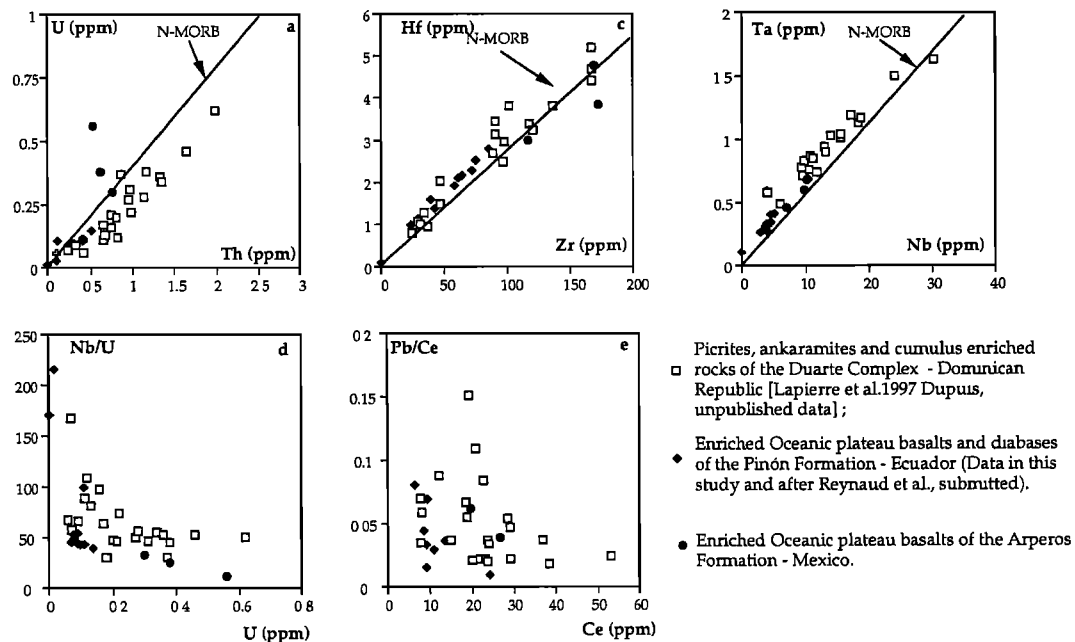


Figure 7. U-Th, Hf-Zr, Ta-Nb, Nb/U-U, and Pb/Ce-Ce plots for the igneous rocks from Dominican Republic, Ecuador, and western Mexico.

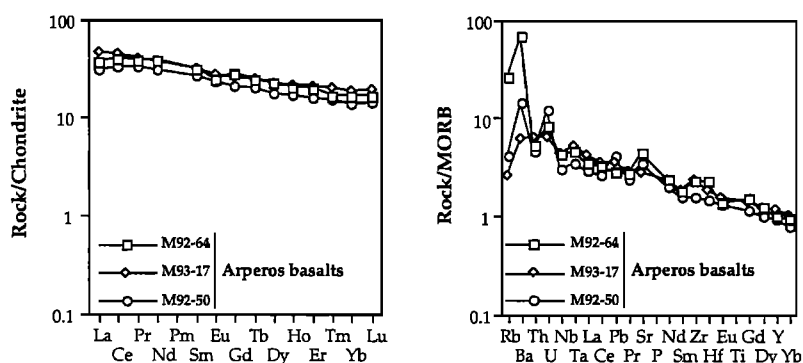


Figure 8. Chondrite-normalized (N) rare earth and NMORB normalized trace element patterns of the basalts of the Arperos Formation (westerncentral Mexico) which show oceanic plateau affinities. Chondrite and NMORB values are from *Sun and McDonough* [1989].

5. Characteristics of Calculated Melts in Equilibrium With cpx

In order to determine the compositions of the cpx parent magmas, REE compositions of melts in equilibrium with these minerals were calculated using the partition coefficients of *Hart and Dunn* [1993]. The REE abundances of these calculated melts based on 97VD55 and 96VD126 cpx compositions of the Duarte basalts (Figure 9) match well with those of the cpx-rich basalt 96VD106 (Figure 5a). The REE composition of the calculated melt based on 97VD55 cpx composition is rather similar to those of both cpx-rich basalts. The calculated melt in equilibrium with 96VD126 cpx composition has a similar LREE-enriched pattern associated with higher REE abundances and a positive Ce anomaly, which is absent in the Mg-rich rocks. The liquid in equilibrium with the 97VD55 cpx has a composition similar to that of the cpx-rich basalt (96VD106). The higher REE abundance of the calculated melt based on

96VD126 cpx is probably related to olivine crystallization leading to a more fractionated residual liquid in the cumulus-enriched rock.

The REE pattern of the calculated melt, based on the SJ40 cpx of the gabbro from Ecuador (using again partition coefficients from *Hart and Dunn* [1993]) is more or less flat (Figure 9) and similar to those of the Piñon diabases (Table 2 and Figure 5b) but displays negative spikes for Ce and Nd which are absent in the REE patterns of the Piñon diabases. However, cpx SJ40 was probably in equilibrium with an enriched tholeiitic magma characterized by a flat REE pattern, similar to those of the Piñon diabases.

In summary, the rocks from Dominican Republic, Ecuador, and western Mexico have general oceanic plateau basalts affinities but show differences in trace element compositions. The Duarte Mg-rich rocks are enriched in LREE, Pb, Th, and U and are characterized by high Th/U ratios. Relative to NMORB, they are depleted in HREE and Y. In contrast, the Piñon diabases have flat REE patterns and are Pb, Zr, and Hf depleted.

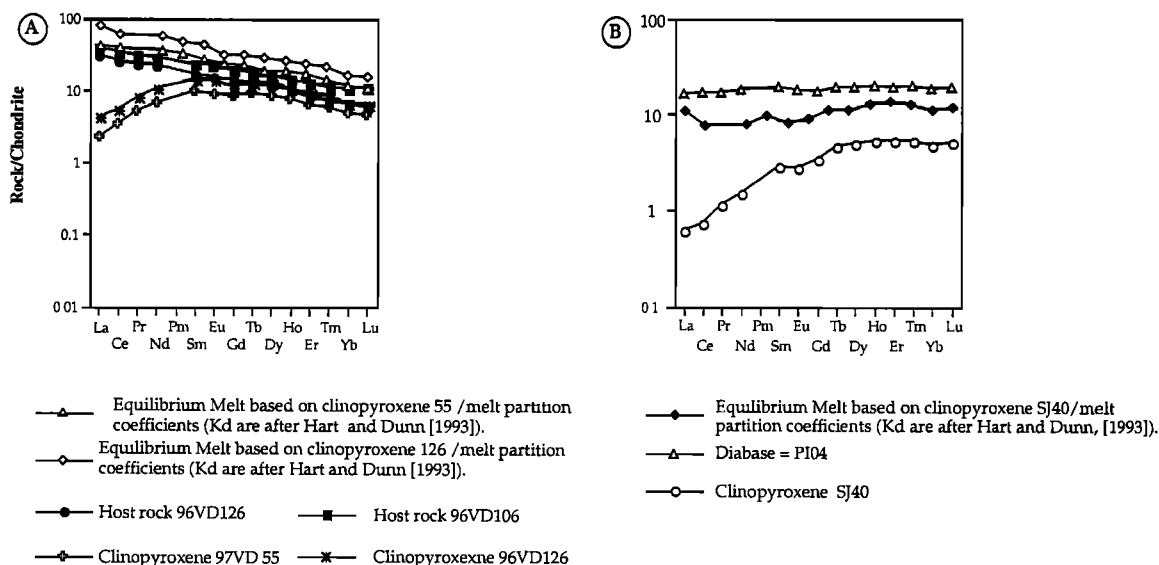


Figure 9. Rare earth patterns of calculated melts in equilibrium with the Duarte (Dominican Republic) and Piñon (Ecuador) clinopyroxenes. Chondrite values are from *Sun and McDonough* [1989].

Their Th/U ratios are low. The Duarte cpx is less LREE depleted than that of Ecuador and is in equilibrium with a cpx-rich basaltic melt, similar to 96VD106. The cpx from Ecuador is in equilibrium with an enriched tholeiitic melt. The Arperos basalts exhibit intermediate geochemical features between those of the Duarte and Piñón rocks.

6. Isotopic Chemistry of the Mineral Separates and Host Rocks

6.1. The cpx-Rich Basalts of the Duarte Complex

As already mentioned, all data were corrected for in situ decay assuming an age of 86 Ma for this formation. The 96VD126 cpx and its cumulate-enriched cpx-rich host rock have similar ϵ_{Nd} ratios (+8.34 and 8.53, respectively; Table 3 and Figure 10) while that of the amphibole is slightly lower (7.99). In contrast, the $(^{87}\text{Sr}/^{86}\text{Sr})_i$ of the amphibole and its host rock are exactly the same (0.70315; Table 3) and plot in the same range as the associated cpx (0.70320). The cpx-rich basalt, cumulus-enriched rocks (97VD55, 96VD121) and their constituent cpx have rather homogeneous ϵ_{Nd} (+7.6 < ϵ_{Nd} < 6.2; Table 3) which are significantly lower than those of the 96VD126 rock and constituent minerals. The cpx of the cpx-rich basalt (96VD106) differs from the previous rocks by having a slightly lower ϵ_{Nd} ratio (+5.5; Table 3 and Figure

10), although its host rock displays ϵ_{Nd} (+6.4) in the same range as other sampled rocks of this complex.

Similarly, the initial Sr isotopic ratio of the 96VD106 cpx is slightly higher (0.70362; Table 3) than that of the corresponding whole rock (0.70370; Table 3). We attribute this difference to the presence of actinolite which locally rims the cpx. These Mg-rich rocks and their minerals (with the exception of the cumulus-enriched 96VD121) have homogeneous $(^{87}\text{Sr}/^{86}\text{Sr})_i$ (0.70315 < $(^{87}\text{Sr}/^{86}\text{Sr})_i$ < 0.70370; Table 3 and Figure 10), which probably reflects their source composition.

Initial lead isotopic compositions of whole rocks and mineral separates from Mg-rich basalts of the Duarte Complex display a limited range of $^{206}\text{Pb}/^{204}\text{Pb}$ (18.97–19.54), $^{207}\text{Pb}/^{204}\text{Pb}$ (15.52–15.60), and $^{208}\text{Pb}/^{204}\text{Pb}$ (38.6–39.3) (Table 3 and Figure 11). These highly radiogenic isotopic compositions fall within the range of enriched OIB signatures. Interestingly, the Duarte Complex domain falls close to or on the Northern Hemisphere Reference Line (NHRL [Zindler and Hart, 1986]) in the $^{207}\text{Pb}/^{204}\text{Pb}$ – $^{206}\text{Pb}/^{204}\text{Pb}$ isotope diagram but on or slightly above the NHRL in the $^{208}\text{Pb}/^{204}\text{Pb}$ – $^{206}\text{Pb}/^{204}\text{Pb}$ isotope diagram.

6.2. Basalts, Diabases, and Cumulate Gabbro From Ecuador and Mexico

In an attempt to obtain a reliable constraint on the age of the Piñón suite, we determined a Sm/Nd internal isochron on

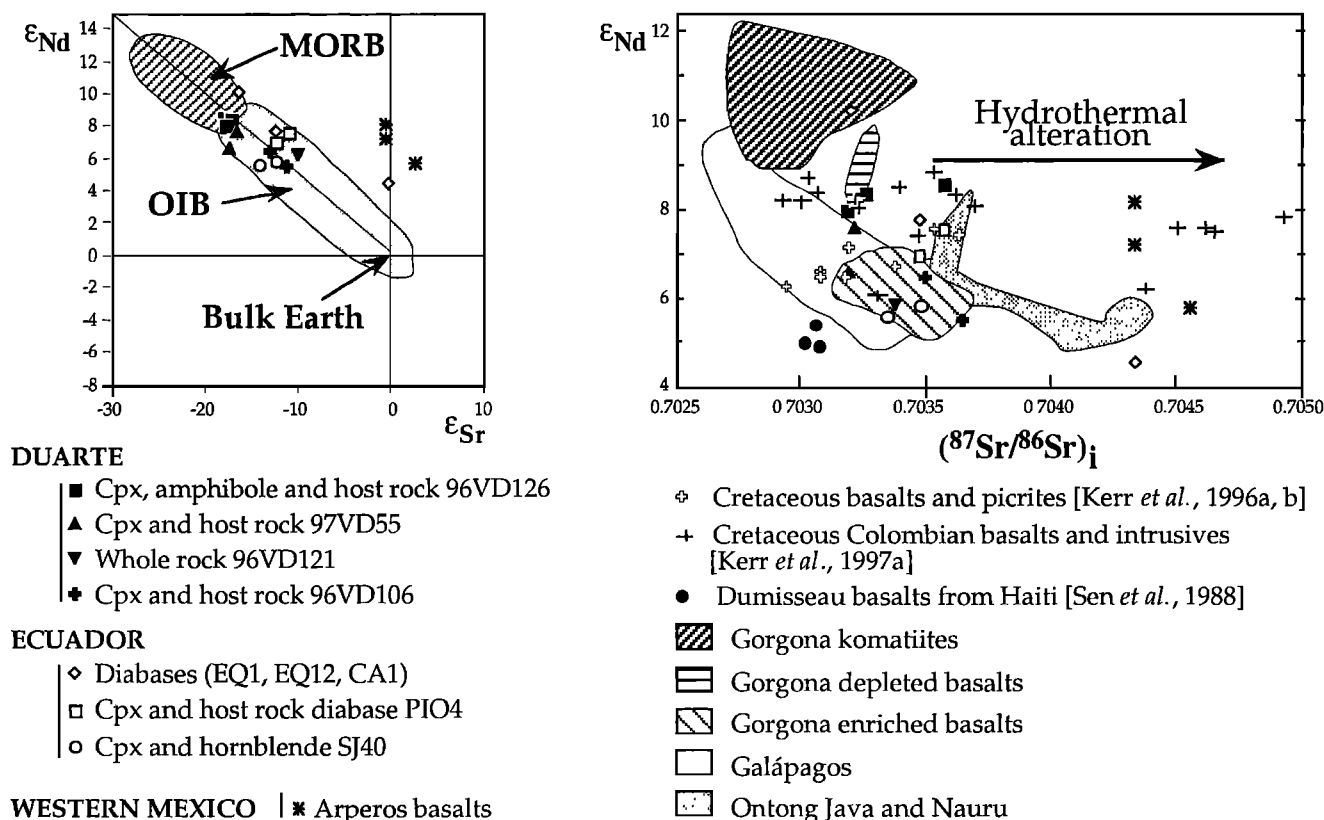


Figure 10. The ϵ_{Nd} – ϵ_{Sr} and ϵ_{Nd} – $(^{87}\text{Sr}/^{86}\text{Sr})_i$ plots for the minerals and host rocks from Dominican Republic, Ecuador, and westerncentral Mexico.

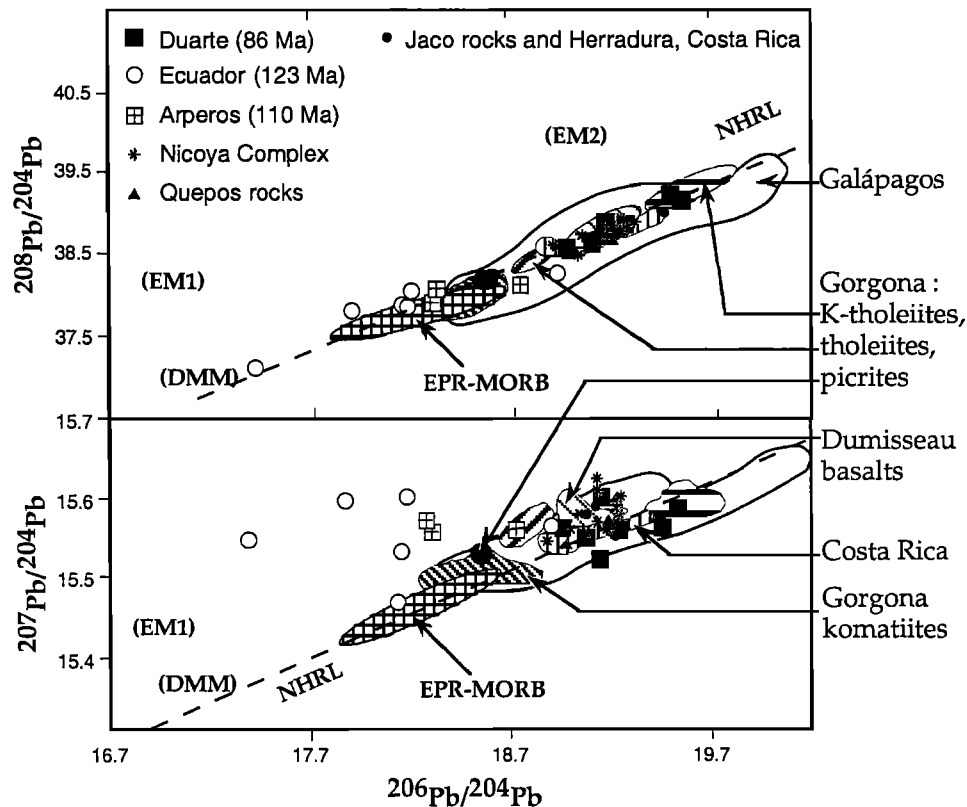


Figure 11. The $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ correlation diagrams for the minerals and host rocks. Recalculated initial ratios have been reported for minerals and whole rocks from cumulates and clinopyroxene-rich basalts from Dominican Republic (86 Ma), gabbros and diabases from Ecuador (123 Ma), and pillow basalts from Arperos from Mexico (110 Ma). Typical analytical uncertainties are indicated by the size of the symbols. Various analytical points and data fields have been reported from the literature. Data from the Nicoya Complex, Jaco rocks and Herradura, Costa Rica (90 Ma), are after *Hauff et al.* [1997], and *Sinton et al.* [1997 and 1998]. The Gorgona picrites, komatiites; tholeiites; and K-tholeiites fields are after *Dupré and Echeverria* [1984]. The field of the Dumisseau basalts from Haiti field is from *Sen et al.* [1988]. The Galápagos lavas field is reported by *White et al.* [1993]. East Pacific MORB data and Galapagos Islands field are from *White et al.* [1987, 1993].

the SJ13 amphibole gabbro (Table 4). The three experimental points (whole rock, plagioclase, and amphibole) yield a regression age of 123 ± 13 Ma with a $^{143}\text{Nd}/^{144}\text{Nd}$ initial ratio of 0.512875 ± 37 (mean square of weighted deviation, $\text{MSWD} = 2.05$) [*Ludwig*, 1987] (Figure 12). This age is interpreted as corresponding to the crystallization of the cumulate gabbro in the oceanic plateau section, now exposed in Ecuador. It also indicates that plateau-building eruptions occurred in the Ecuadorian province as early as 123 Ma. Meanwhile, the rather large uncertainty of this age needs to be refined by additional analyses.

In common with the minerals and host rocks of the Duarte Complex the diabases, basalts, gabbro, and associated cpx from Ecuador and Mexico share rather similar homogeneous ϵ_{Nd} ratios that range between +8 and +5.8 (Table 3) (*Reynaud et al.*, submitted manuscript, 1998). The SJ40 plagioclase has a slightly lower ϵ_{Nd} (+4.62, Table 3). However, a diabase (EQ1) and a basalt (CA1) from Ecuador have higher ($\epsilon_{\text{Nd}} = +10$) and lower ($\epsilon_{\text{Nd}} = +4.5$) ratios, respectively (Table 3 and Figure 10). This suggests that the basalts and diabases from Ecuador and Mexico might be derived from different mantle sources and/or different blends of depleted NMORB and enriched OIB magma types.

In the ϵ_{Nd} versus ϵ_{Sr} diagram (Figure 10), all these rocks fall within the "mantle array," and their $(^{87}\text{Sr}/^{86}\text{Sr})_i$ likely reflects the source composition, with the exception of three basalts from western Mexico (M92-64, M93-17, and CA1). The shift of the Sr isotopic ratios of these three rocks toward the radiogenic side of the mantle plot reflects an enrichment in radiogenic Sr (Figure 10), probably induced by seawater contamination through hydrothermal process or contamination with pelagic sediment [*Kerr et al.*, 1997b].

Lead initial isotopic compositions of whole-rocks and mineral separates from basalts and cumulate gabbros from Ecuador and Mexico have a large range of $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios (Table 3 and Figure 11). Diabase EQ12 has a markedly lower $^{206}\text{Pb}/^{204}\text{Pb}$ ratio and plots near the depleted mantle MORB (DMM) source. In contrast, CA1 has a significantly higher $^{206}\text{Pb}/^{204}\text{Pb}$ ratio similar to those of recent Galápagos lavas. The Ecuador samples define a nearly horizontal domain located slightly above the NHRL in the $^{207}\text{Pb}/^{204}\text{Pb}$ diagram. These high $^{207}\text{Pb}/^{204}\text{Pb}$ ratios could reflect a contamination of their mantle sources by pelagic sediments [*Doe*, 1970] and/or altered oceanic crust.

In summary, all samples from Dominican Republic, Ecuador, and western Mexico have fairly homogeneous ϵ_{Nd}

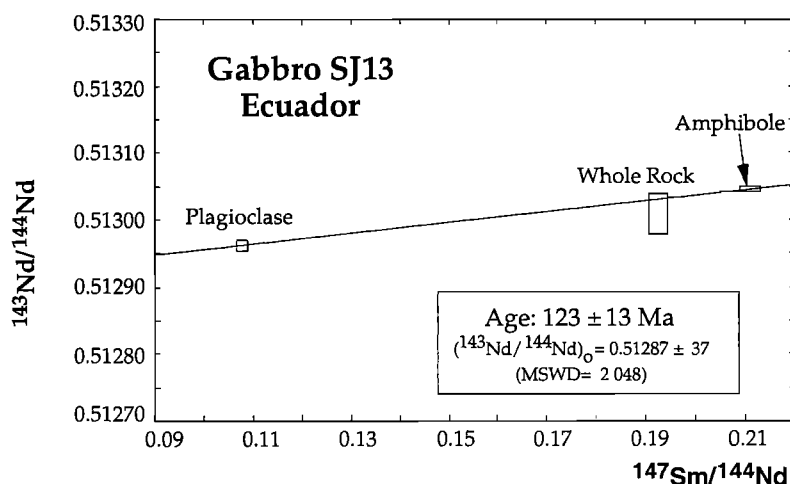


Figure 12. Sm/Nd isochron plot for minerals and whole-rock from the Ecuadorian SJ13 Gabbro. The regression analysis [Ludwig, 1987] yields $T = 123 \pm 13$ Ma, $(^{143}\text{Nd}/^{144}\text{Nd})_0 = 0.51287 \pm 37$, $\epsilon\text{Nd}_0 = +7.76$, and $\text{MSWD} = 2.05$ for plagioclase, whole rock and Amphibole.

(+5.5 to +8), similar to those of oceanic plateau basalts. The cpx of the Duarte cumulus-enriched basalt has slightly higher ϵNd (+8.5). Finally, one mafic rock of the Piñón Formation has the highest ϵNd (+10), similar to those of NMORB. A comparison of initial Pb isotopic signatures measured (on mineral separates and host rocks) on cumulus-enriched Mg-rich basalts from the Duarte Complex, on gabbros and diabases from Ecuador, and on Arperos basalts from Mexico emphasize a contribution from a more depleted mantle source for Ecuador than for the Duarte Complex. Mg-rich basalts from the Dominican Republic (Duarte) have a Pb isotopic range consistent with that of the Galápagos HIMU plume component and similar to the Gorgona tholeiites and Costa Rican lavas [White *et al.*, 1993; Dupré and Echeverría, 1984; Hauff *et al.*, 1997; Sinton *et al.*, 1997]. The Ecuadorian and Mexican basalts and cumulate gabbros have a Pb isotopic signature intermediate between NMORB and OIB components.

7. Discussion: Presence of Three Distinct Magmatic Suites in the CCOP

A major difficulty in constraining the geochemical and isotopic characteristics of oceanic plateau igneous rocks arises from the low grade metamorphism or hydrothermal alteration that these rocks suffered either during their magmatic emplacement and cooling in a submarine environment and/or during their subsequent tectonic emplacement. These processes resulted in the mobility of Rb, Sr, and U, as suggested by the variable behavior observed for these elements in most spidergrams (Figure 6), despite the fact that in this study we have deliberately chosen to focus our geochemical and isotopic investigations on a restricted number of samples and host minerals showing minimum alteration. However, the observation that most whole rock REE patterns fit with those calculated from the compositions of separated primary cpx indicates that the REE distribution was not significantly affected by postmagmatic processes. In addition, the analysis of separates of unaltered primary minerals allows us to check that the corresponding bulk rock compositions did not suffer

noticeable Nd and Pb (and, in most cases, Sr) isotopic changes related to hydrothermal alteration (i.e., 96VD126 and SJ40, Table 3).

On the basis of ages, rock types, and geochemical and isotopic results the ultramafic-mafic oceanic crustal fragments currently regarded as belonging to the CCOP appear to belong to three distinct magmatic suites. The Upper Cretaceous suite (92–86 Ma) comprising the Gorgona basalts is the best known and geochemically well characterized. It makes up the basement of the Caribbean Sea and part of the numerous accreted oceanic crustal fragments exposed along the Pacific coast of Central America (Costa Rica) and South America (Colombia) and in the Caribbean (Dominican Republic, most of Duarte Complex; Curaçao, and Aruba; Figure 1). The basalts and diabases have LREE-enriched to flat REE patterns and differ from NMORB by their enrichments in Ti, Nb, Th, and Ta. Initial radiogenic Nd isotope ratios have a rather restricted compositional range ($\epsilon\text{Nd} = +6$ to $+9.5$ [Sen *et al.*, 1988; Kerr *et al.*, 1996b, 1997b; Alvarado *et al.*, 1997; Hauff *et al.*, 1997; Sinton *et al.*, 1997]). Similarly, all these rocks have a Pb isotopic signature consistent with the field defined by the recent Galápagos Islands, suggesting the contribution of a HIMU component (Figure 11).

The age of the second suite, composed of the Ecuadorian and Mexican oceanic rocks, is Early Cretaceous (123–91 Ma). The corresponding rocks have a wide range of initial radiogenic Nd and Pb isotopic ratios, intermediate between OIB and NMORB components. The Ecuadorian igneous rocks, compared to those of the Dominican Late Cretaceous Duarte Complex, are depleted in the most incompatible elements.

Finally, in the Duarte and Nicoya Complexes (Figure 1), slices of Upper Jurassic oceanic rocks are tectonically associated with the Upper Cretaceous oceanic plateau tholeiites. Indeed, these Upper Jurassic basalts and diabases from Dominican Republic differ from the Duarte cpx-enriched and/or cpx-poor basalts because they are depleted in LREE and in most incompatible trace elements [Lapierre *et al.*, 1999]. Thus these basalts and diabases are interpreted as remnants of the Late Jurassic Caribbean oceanic crust formed at a ridge and possibly close to a hotspot.

In Costa Rica, Upper Jurassic radiolarian cherts were probably deposited on the top of oceanic crust [Sinton *et al.*, 1997]. In Hispaniola, slices of Upper Jurassic oceanic crust are tectonically associated with the Late Cretaceous Duarte Complex (see section 6).

In summary, at least two major pulses of oceanic plateau magmas occurred in the CCOP: Late Cretaceous (88–92 Ma) and Early Cretaceous (100–123 Ma). The Late Cretaceous cpx-rich basalts share the HIMU affinity of the Galápagos hotspot, while those of the Early Cretaceous plutonic and volcanic rocks are intermediate between depleted and HIMU mantle sources.

8. Geodynamic Implications

The presence of two distinct oceanic plateau suites in the crustal fragments of the peri-Caribbean realm raises two questions.

1. Are these suites derived from two distinct hotspots possessing different signatures, as suggested by Kerr *et al.* [1997a], or solely from the Galápagos one?

2. If they are both derived from the Galápagos hotspot, is the present-day geographic location of the Ecuadorian and Mexican Early Cretaceous oceanic terranes consistent with the locations of the Galápagos plume and South America and the direction of Farallon plate motion during the Early Cretaceous, respectively?

If both suites are linked to the Galápagos plume this implies that (1) the activity of the Galápagos plume began at least in Early Cretaceous times (or even before); (2) its isotopic composition has changed markedly with time from low to high $^{206}\text{Pb}/^{204}\text{Pb}$ values; (3) it was heterogeneous and different parts were tapped in different places; and (4) its location was possibly close to or on a ridge, similar to that of the Iceland plume; [Kerr *et al.*, 1995]. It has been proposed that many of the Pacific plateaus (i.e., Shatsky, Ontong Java, Manihiki) may have been formed above long-lived, near-mid-ocean ridge or ridge-centered Cretaceous hotspots (140–65 Ma) [Mahoney, 1987]. Moreover, the Pb isotopic composition of the hotspot may change with time, i.e., the source of the Ontong Java plateau lavas shows an evolution with time from lower to higher $^{206}\text{Pb}/^{204}\text{Pb}$ ratio [Mahoney *et al.*, 1993].

The Ecuadorian and Mexican igneous terranes (1) could reflect an early stage of the Galápagos hotspot activity which would have lasted from 123 Ma to 86 Ma, or (2) could have formed from a possible precursor which would have been only active during a short time at the early Cretaceous or alternatively could have formed somewhere other than at the Galápagos hotspot.

Some plate tectonic constraints are important in this discussion. For example, the development of a magmatic arc through Ecuador and Colombia during the Jurassic suggests that the Farallón plate was subducting southeastward under the northwestern margin of South America [Aspden *et al.*, 1987; Jaillard *et al.*, 1995]. However, during the latest Jurassic (\approx 140–135 Ma) the activity of the continental magmatic arc stopped in Ecuador and Colombia and a new magmatic arc developed along the Peruvian margin [Aspden *et al.*, 1987; Jaillard *et al.*, 1995]. This feature suggests that the subducting motion of the Farallón Plate beneath South America drastically changed toward a NNE motion during the latest Jurassic, and

this motion persisted until Late Cretaceous times (\approx 80 Ma) [Jaillard *et al.*, 1995]. If the Ecuadorian Early Cretaceous oceanic or older plateau fragments had been derived from the Galápagos hotspot, they should be presently located far NNE from the present-day Galápagos Islands. Therefore they are more probably linked to another hotspot, which was located much farther southwest of the South American plate than the Galápagos. In contrast, the Early Cretaceous accreted oceanic plateau fragments from western Mexico could have formed at the Galápagos hotspot.

The Late Cretaceous (92–86 Ma) crustal oceanic fragments exposed presently in Costa Rica (Nicoya Peninsula), in the Caribbean region (Dominican Republic, Curaçao, Aruba), and in the Western Cordillera of Colombia are characterized by a rather large range of ϵ_{Nd} ratios (+9 to +6) and a limited range of lead isotopic compositions that fall within the field of the recent Galápagos Islands. This suggests that the Late Cretaceous (92–86 Ma) oceanic fragments were most probably linked to the igneous activity of the Galápagos plume, whereas the hotspot from which the oldest fragments were derived remains unknown. More data are needed to geochemically characterize the fragments of the CCOP and to understand its chronological and geodynamic development.

9. Conclusions

The oceanic plateau fragments of the CCOP exposed in central Mexico, Dominican Republic, and coastal Ecuador belong to two distinct suites which differ in their age and trace element and isotopic chemistry.

1. The minerals and cumulus-enriched host rocks of the Duarte Complex (Dominican Republic), dated at 86 ± 1.4 Ma, have LREE-enriched patterns; moderate enrichments in large ion lithophile elements (LILE); high Nb, Ta, and Pb contents; homogeneous ϵ_{Nd} ratios (+8 to +5) and radiogenic Pb isotopic compositions, very similar to the Galápagos HIMU component. They are geochemically similar to the Late Cretaceous mafic and ultramafic rocks (with the exception of the Gorgona komatiites, picrites from SW Colombia [Kerr *et al.*, 1997a]) of the CCOP and likely derived from the Galápagos hotspot.

2. The Early Cretaceous (> 91 Ma) diabases and basalts (Piñón Formation) and cumulate gabbros (123 Ma) from western Ecuador differ from the Duarte Mg-rich rocks by flat REE patterns and lower Pb, Zr, Hf, Th, and U contents. The Lower Cretaceous basalts and diabases from Mexico (Arperos Formation) exhibit intermediate trace element compositions between the Duarte and Piñón rocks. Both Ecuadorian and Mexican rocks have also a wider range of ϵ_{Nd} and Pb isotopic ratios that range between those of NMORB or depleted plume and HIMU sources. Geochemical constraints alone are not really conclusive because there is ample evidence for geochemical variability of magmas originating from a single plume but derived from variable melting degrees of heterogeneous sources [Arndt *et al.*, 1996; Kerr *et al.*, 1996a]. These geochemical features of the Ecuadorian and Mexican mafic rocks suggest that they derived from a ridge-centered, or near ridge hotspot.

The Caribbean-Colombian plateau was likely formed during two major pulses of Late Cretaceous and Early Cretaceous, respectively. The Late Cretaceous pulse is likely linked to the

Galápagos hotspot whereas that of Early Cretaceous probably derived from a near-ridge hotspot, located farther SW of South America, somewhere in the SE Pacific.

Acknowledgments. We would like to thank R. J. Arculus for his very helpful comments on the manuscript, P. Brunet (UMR 5563) who did all the Sr-Nd TIMS analyses, and J. Cotten (UMR 6538) for ICP-AES analyses. This work was funded by the CNRS teams UPRES-A 5025, UMR 6526, UMR 6538, UMR 5567, UMR 5563 and has benefited from MENESR-DSPT3, FNRS 21-31216.91 grants to R. C. Maury and J. Hernandez, respectively.

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(Received March 4, 1998; revised October 19, 1998; accepted October 26, 1998.)