

THE DISTRIBUTION OF IGNEOUS ROCK SUITES THROUGHOUT THE CARIBBEANTHOMAS W. DONNELLY & JOHN J. W. ROGERS²

ABSTRACT

Donnelly, T. W. & J. J. W. Rogers (1978). The distribution of igneous rock suites throughout the Caribbean. *In*: H. J. Mac Gillavry & D. J. Beets (eds.): The 8th Caribbean Geological Conference (Willemstad, 1977). *Geol. Mijnbouw*, 57, p. 151-162.

New analytical determinations for more than one hundred igneous samples enable us to place several circum-Caribbean igneous series into a tentative tectonic perspective. We consider that the basaltic rocks from Curaçao, Aruba, Tiara (Venezuela), and the mafic intrusives of the Paraguaná Peninsula (Venezuela) belong to a MORB association of possible early Late Cretaceous age, which is correlative with basinal basalts from the Caribbean, and which has been tectonically emplaced after eruption on to the continental border. Some stratigraphically early volcanic complexes from Jamaica, Dominican Republic, Désirade, Tobago, and Bonaire are placed in the primitive group, along with the early volcanics of Puerto Rico and the Virgin Islands. Plutonic rocks from Haiti and the Pedro Bank are somewhat high in K but not broadly different from those of Puerto Rico. The young volcanics of the central Dominican Republic are of the shoshonite (high-K) group. The plutonics of the southern Caribbean continental borderland are probably all calcalkaline, including those of Tobago. Several are notably high in cobalt, which further demonstrates that the southern Aves Ridge plutonics belong here and are not part of some other series.

INTRODUCTION

An earlier investigation into the diversity of igneous rock types (DONNELLY ET AL., 1971) demonstrated two fundamentally different island-arc magma series in the Puerto Rico-Virgin Islands area. Subsequent studies (DONNELLY ET AL., 1973; DONNELLY & ROGERS, in press) increased the variety of minor element criteria for differentiation of the two series and also showed that tectonically allochthonous MORB basalts could be recognized. The present study examines plutonic rocks and basalts from the southern Caribbean, early island-arc igneous rocks and very young volcanic rocks from the Dominican Republic, and some volcanic and plutonic rocks from Jamaica, Haiti, the Aves Ridge, and Tobago (Fig. 1). Each of the major suites recognized in the earlier studies is found elsewhere in the Caribbean, and the occurrences have significance in the interpretation of Cretaceous Caribbean tectonics. Most of the rock units reported here are incompletely studied, inviting further investigations.

The igneous rock series recognized in the earlier papers are discussed in more detail by DONNELLY & ROGERS (in press) and include: (1) calc-alkaline (CA) including a high-potassium (HK) variant identifiable with so-called shoshonites elsewhere; (2) primitive island-arc (PIA), which is essentially the same as what has been called island-arc tholeiite (JAKEŠ & GILL, 1970); (3) MORB, or mid-ocean ridge basalt; and (4) a diabase dike-swarm group.

The calc-alkaline group is very similar to well-known and widespread island-arc igneous suites located around the Pacific margin. It contains a spectrum of silica contents, with andesite prevalent over either basalt or dacite, and incompatible minor elements tend to increase sharply with increased SiO₂. The primitive suite resembles oceanic basalts in the low content of incompatible minor elements, but has abundant siliceous differentiates not greatly enriched in these elements, and also low Ti, REE, Mg, Ni, and Zr compared to oceanic basalt. The Caribbean MORB suite is quite indistinguishable chemically and isotopically from ordinary MORB, but it does not appear to have been emplaced at an accreting plate boundary. The diabasic suite is only recognized in the Puerto Rico-Virgin Islands area and will not be discussed in this paper.

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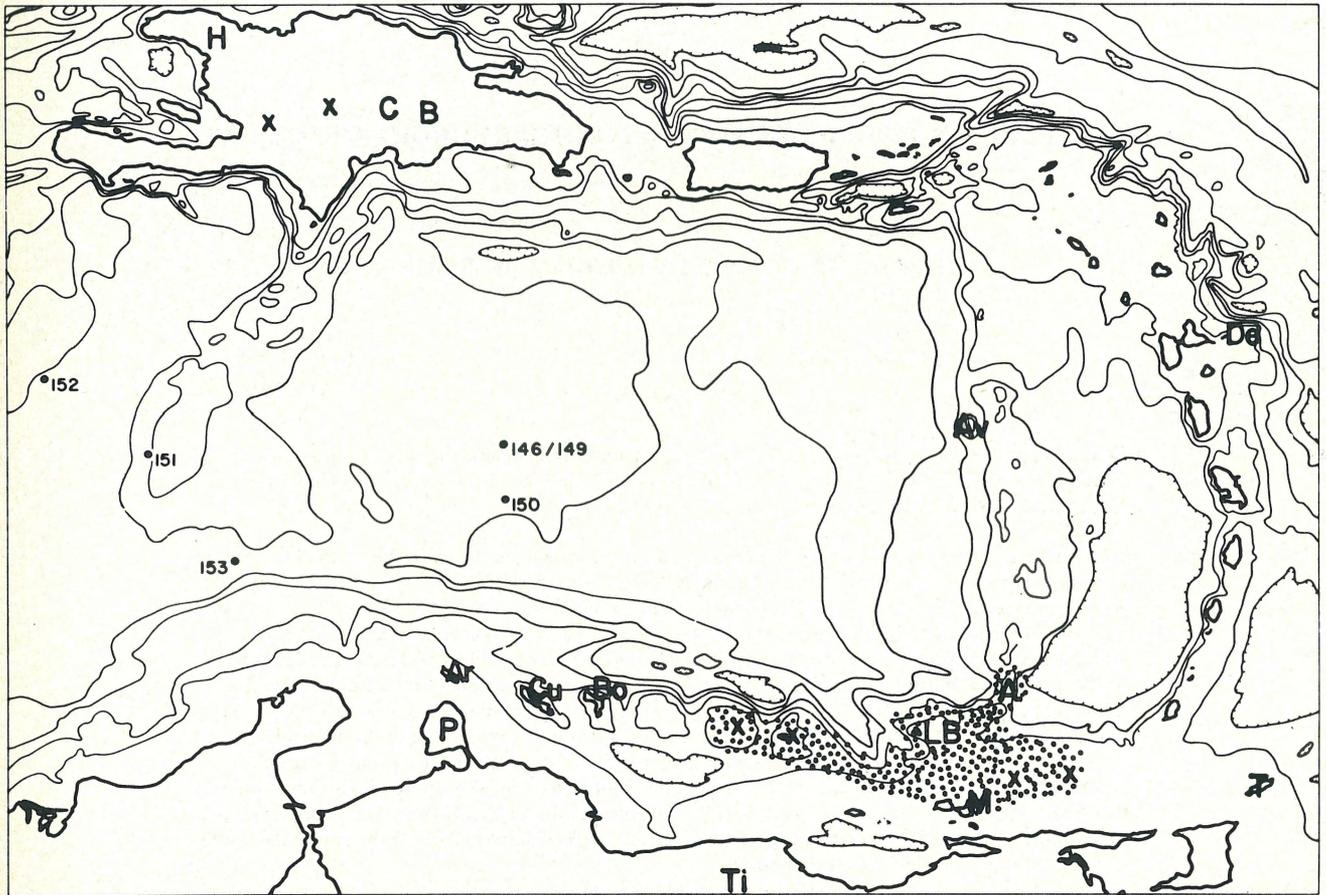


Fig. 1
Location map of the eastern Carribean.

Symbols
for Hispaniola: H = Terre Neuve; C = Constanza; B = Bonao District. for Haiti (Woodring et al., 1924) and the Dominican Republic (MacDonald & Melson, 1969); x = igneous provinces.
De = Désirade; Av = Aves Ridge dredge haul 12 (Nagle, 1972); P = Paraguaná; Ar = Aruba; Cu = Curaçao; Bo = Bonaire; Ti = Tiara Lavas; A = Aves Ridge dredge haul 1317 and 1318 (Fox et al., 1971); LB = La Blanquilla; M = Margarita; T = Tobago.
Stipple pattern connects occurrences (x's and letters) of plutonic rocks, with letter symbols for high-cobalt rocks.

THE OCCURRENCE OF MORB IN THE CARIBBEAN

The identification of the Bermeja complex as typical MORB and the discovery during the Leg 15 Deep Sea Drilling in the Caribbean of widespread late Cretaceous MORB in the Venezuelan and Colombian Basins have raised interesting questions about the occurrence of basaltic rocks elsewhere around the Caribbean margin. The Curaçao Lava Formation (BEETS, 1972, 1975), was identified with the basal MORB in chemistry (DONNELLY ET AL., 1973, BEUNK & KLAVER, 1977) if not in age (SANTAMARIA & SCHUBERT, 1974).

The chemical characteristics of MORB are too well known to need elaborating here, but the distinction between MORB and the PIA rocks is less well understood. MORB has been sufficiently thoroughly sampled and studied to state with a high degree of confidence that it rarely differentiates to a rock as siliceous as andesite; it is commonly but not invariably light

rare earth depleted; and it almost invariably has very low K and moderate Ti and Mg contents. The recent discovery of lower Ti and Mg varieties slightly complicates the task of differentiating this rock from the PIA rocks, which are nearly invariably lower in these elements.

In the absence of exhaustive minor-elements and isotopic data, the distinction between MORB and PIA is even more difficult. The present study focuses on several areas of distinction, none of which is strictly applicable to single specimens but lend themselves to the study of a suite of specimens. The U/Th relationships (Fig. 2) which serve so admirably to differentiate PIA and CA rocks are of little value in differentiating MORB and PIA, which have similarly low values. PIA rocks do tend to be higher in K than MORB, but low-grade metamorphism may obscure this difference and recently drilled altered western Atlantic Cretaceous MORB (unpublished data) show that spectacularly high values of K can be found in

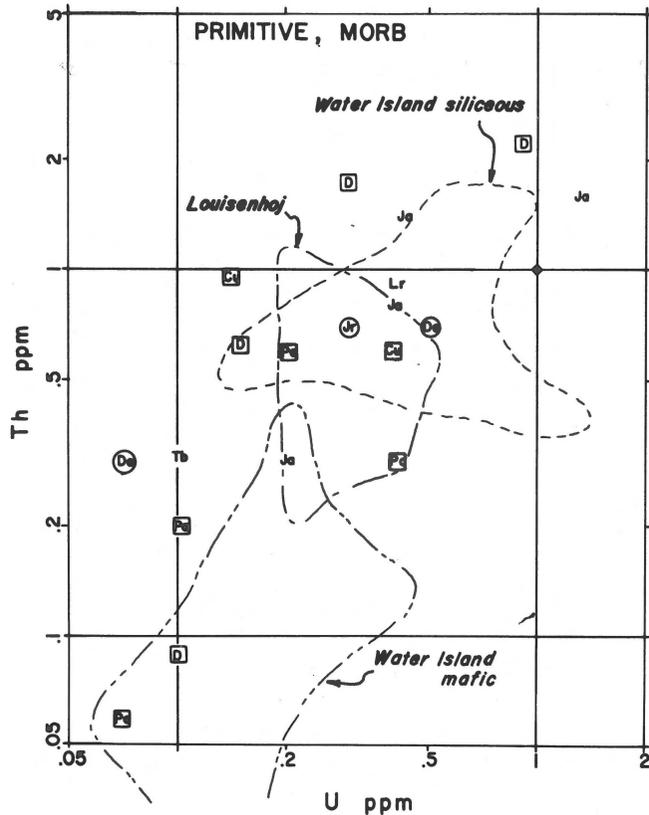


Fig. 2
Log Th vs Log U for PIA (circles) and MORB rocks (squares). Fields of Virgin Island PIA rocks are indicated.

Letter Symbols (also used for Figs. 3-10):

A = Aves Ridge dredge hauls; andesites from northern loc. in Fig. 9 and gabbros from southern loc. in Fig. 5; C = Constanza volcanics, Dominican Republic; D = drilled basalts and dolerites from Venezuelan Basin, Leg 15, Deep Sea Drilling Project; De = Désirade; F = Los Frailes; H = Terre Neuve plutonic rocks, Haiti; J = drilled mafic plutonic rock from Santa Cruz Mts., Jamaica; Ja (Jac, Ja1, Ja2 for individual samples) = Arthur's Seat volcanics, Jamaica; Jr = Devils Race Course volcanics, Jamaica; Js = Summerfield Formation, Jamaica; Lr = Los Ranchos volcanics, Dominican Republic; M = Maimón volcanics, Dominican Republic; P = drilled plutonic from Pedro Bank; Pa = Paraguán Peninsula; S = plutonic rocks from Venezuelan margin and offshore islands; Tb = Bacolet breccia, Tobago; Tn = foliated tonalite, Dominican Republic (Bonaó District); To = plutonic rocks, Tobago; Tr = Tíreo Formation, Dominican Republic; V = Villa de Cura volcanics, northern Venezuela.

this rock type. The total alkali is consistently higher in unmetamorphosed PIA rocks, as shown by the distribution of points on the FMA diagram (Fig. 3). More useful for discrimination is the fact that PIA commonly differentiates to very siliceous varieties (Fig. 4). An additional criterion is the behavior of Ti. In MORB, Ti remains in the melt, increasing with Fe/Mg (Fig. 5) and remaining coherent with Zr. In PIA rocks, Ti behaves independently both of Fe/Mg (Fig. 6) ratios and of Zr content (DONNELLY & ROGERS, in press); evidently it is removed from the melt into another, as yet unidentified phase

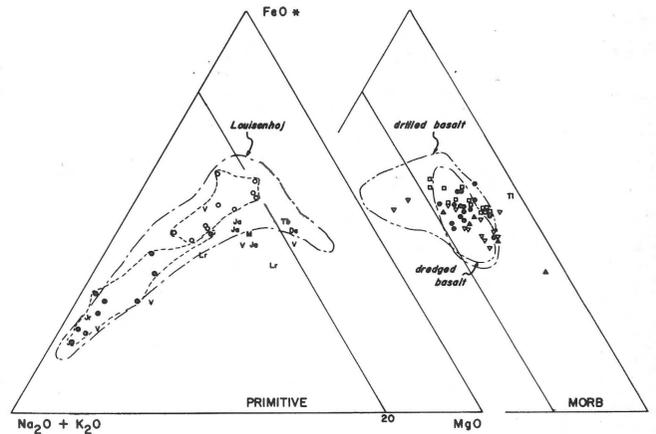


Fig. 3

FMA diagram for PIA and MORB rocks. Symbols as in Fig. 2, except that small circles indicate Bonaire basalts and porphyrites (unlabeled fields); open squares = Leg 15 DSDP basalts; solid circles = Aruba basalts; open inverted triangles = mafic rocks from the Paraguán Peninsula; solid triangles = Curaçao mafic rocks. Fields of Louisenhoj Fm. (virgin Islands), 85% of drilled oceanic basalts, and 89% of dredged oceanic basalts are indicated. The line at $\text{Na}_2\text{O} + \text{K}_2\text{O} = 20\%$ discriminates most of the samples.

(possibly amphibole) during all stages of magma generation and differentiation.

Curaçao and Aruba

A sample from the Curaçao Dry Dock was analyzed thoroughly and reported by DONNELLY ET AL. (1973). The major and minor elements, most notably the REE, were seen to be identical with basinal MORB samples. Additional major element analyses from other specimens from Curaçao and from a large suite from Aruba show that the lava formations of both islands are consistently of this type. The Ti vs. Fe/Mg (Fig. 5) and FMA (Fig. 3) of this suite is very distinctive, and a few Ti/Zr ratios are also consistent. The occurrence of conglomerates above these rocks in Aruba is puzzling but not exceptional; analogous relationships are seen in similar rocks in Guatemala (LAWRENCE, 1975) and Venezuela (PIBURN, 1967). An environment similar to the modern Cayman Trough might be indicated.

Paraguán Peninsula

A suite of plutonic and volcanic rocks from the Paraguán peninsula (MARTÍN & AROZENA, 1973) shows FMA (Fig. 3) and Ti vs. Fe/Mg (Fig. 5) relationships very similar to those of Curaçao and Aruba, except that low-Ti, low-Mg rocks are prominent, thus affording a clearer view of the behavior of Ti during differentiation. Two samples analyzed by us for Th and U (Fig. 2) show typical MORB values.

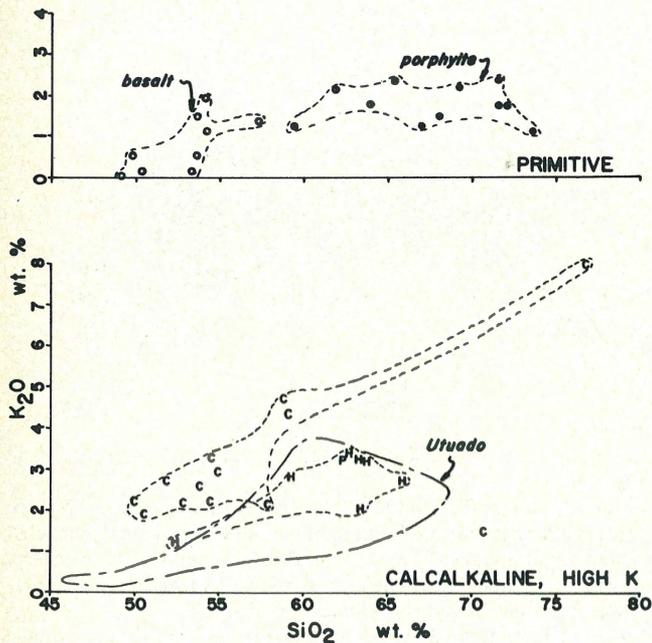


Fig. 4
K₂O vs SiO₂ for Bonaire (top); Constanza volcanics (Dominican Republic) and Haitian and Pedro Bank plutonics (bottom). Field of the Ututodo Pluton (Puerto Rico) is indicated. For letter symbols: see Fig. 2.

Tiara Volcanics

The Tiara volcanics of northern Venezuela (SHAGAM, 1960; PIBURN, 1967) evidently belong to the MORB suite. The few specimens analyzed by us show a MORB behaviour of Ti vs. Fe/Mg (Fig. 5) and Ti/Zr, but clearly more analytical work is needed. It is tempting but unproven to suggest a correlation of the Tiara and the Curaçao-Aruba rocks, but age information (suggesting middle Cretaceous and largely unpublished) is inconclusive.

Discussion

The identification of the mafic rocks of the Venezuelan borderland, the Netherlands Antilles and offshore Venezuelan islands has been the subject of considerable debate. The Dutch workers (BEETS, 1972, 1975; BEETS & MAC GILLAVRY, 1977) have considered these rocks to represent the early stage of an island arc. BEETS (1975) considered the Curaçao and Bonaire basaltic rocks to be correlative, but in later work (BEETS & MAC GILLAVRY, 1977; BEUNK & KLAVER, 1977) the two islands have been seen to have different basement rock types. SANTAMARIA & SCHUBERT (1974) considered the rocks of Curaçao, the Paraganá Peninsula, and some other localities to belong to a tholeiitic suite, distinct from the widespread and younger calcalkaline rocks of the continental margin. However, other than relating the K/Ar ages of these rocks to Early Cretaceous underthrusting of the Caribbean Plate, these

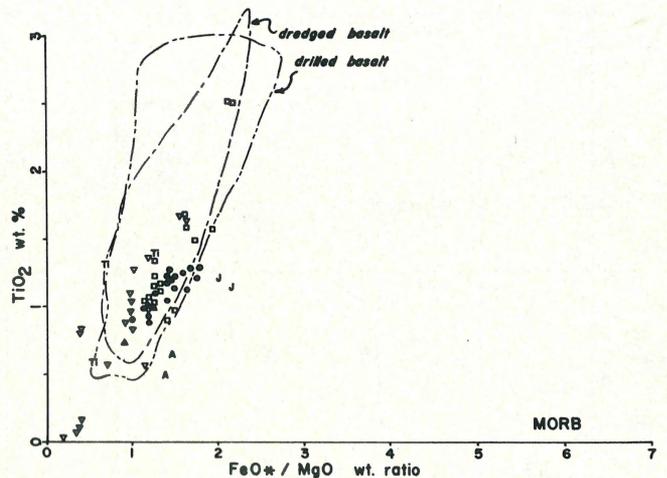


Fig. 5
TiO₂ vs FeO*/MgO ratio, MORB rocks. Fields of dredged and drilled basalts, as in Fig. 3, are indicated. Symbols as in Fig. 3.

authors provide no further tectonic interpretation of this suite.

Referring to our studies in the northeastern West Indies, and our interpretations of analogous rock series in the southwestern Pacific (DONNELLY & ROGERS, in press), we offer a slightly different interpretation. We note first that the MORB suite, which is becoming increasingly narrowly defined as successive oceanic sites are drilled, has not been recognized anywhere to have been erupted on continental material of any thickness. Indeed, the very low values of certain elements, such as K and Rb, as well as the lead and strontium isotopes, would argue strongly against such a site of emplacement. Occurrences of MORB in an island-arc environment, such as the Bermeja Complex of Puerto Rico (DONNELLY ET AL., 1971), and in continental environments, such as the El Tambor Formation of Guatemala (LAWRENCE, 1975), are explained by subsequent tectonic activity. Early volcanic rocks in island arcs have been recognized in several areas (GILL, 1970; DONNELLY & ROGERS, in press; DONNELLY ET AL., 1971; EWART & BRYAN, 1972). Although more variable than MORB, these occurrences have certain distinctive features in common, such as abundant siliceous differentiates, low levels of incompatible elements in these differentiates and relatively low values of the less mobile incompatible elements (such as Th, Zr, and REE) in the mafic rocks. These rocks are succeeded in each instance by the widely recognized calcalkaline suite. Their tectonic environment is not certain, but in some instances (DONNELLY, 1972) these early rocks are erupted in an abyssal environment prior to the existence of an emergent island-arc platform. Whether this eruption occurs during an early phase of compressive tectonic activity is not certain, although the later calcalkaline eruptive phase seems to be clearly compressive.

We suggest that the MORB rocks of Aruba, Curaçao, the Paraganá Peninsula, and, possibly the Tiara volcanics of

Venezuela, are all of original sea-floor origin, and that they are correlative with the MORB recovered in the Venezuelan Basin during Leg 15 deep-sea drilling (DONNELLY ET AL., 1973). The stratigraphic date for the cessation of this episode in the Venezuelan Basin (about 85 m.y.) is younger than radiometric ages within the tholeiitic complex (118-129 m.y., Curaçao and Paraganá only: SANTAMARIA & SCHUBERT, 1974), and we must admit that we know nothing of the age duration of the extensional magmatic episode within the Caribbean. It should be noted that in the western Caribbean, there is an analogous 'discrepancy' between ages above and within this complex. Numerous stratigraphic ages of the overlying material at DSDP site 152 (EDGAR, SAUNDERS ET AL., 1973) in Panama (BANDY & CASEY, 1973), Costa Rica (GALLI OLIVIER & SCHMIDT-EFFING, 1977; STIBANE ET AL., 1977) and Haiti (MAURRASSE ET AL., 1977) suggest a Campanian age for the end of this event, but there are also indications for earlier ages within the complex in Costa Rica (Jurassic-Cretaceous boundary, Costa Rica: GALLI OLIVIER, 1977) and in Haiti (Early Cenomanian or older, MAURRASSE ET AL., 1977).

Pending a resolution of the problem of the age duration of the event, we suggest that all occurrences of MORB both in the basins and on the land belong to the same complex, and that terrestrial occurrences all represent uplift, or, more likely, obduction. The Villa de Cura complex of northern Venezuela has been widely interpreted as a major allochthonous mass which moved southward from the Caribbean borderland during the latest Cretaceous and early Tertiary. The Tiara volcanics (of putative MORB affinities) and the Villa de Cura volcanics (possible PIA series) potentially represent originally oceanic volcanic series transported a considerable distance inland. Regardless of these identifications, the inference of the tectonic transport suggests that the MORB rocks of Paraganá, Aruba and Curaçao may represent similarly transported basinal basalts from the same complex. The gravity data of MARTÍN-BELLIZIA & AROZENA (1972) and SILVER ET AL. (1975) are consistent with this interpretation of allochthony.

THE PRIMITIVE ISLAND ARC SUITE IN THE CARIBBEN

In Puerto Rico and the Virgin Islands, the earliest volcanic rocks (except the obducted Bermeja metamorphosed MORB) belong to an enigmatic series we have called primitive island-arc (PIA). First characterized by lead isotopes and by low U and Th values, even in the abundant siliceous examples (DONNELLY ET AL., 1971) later studies (DONNELLY & ROGERS, in press) showed that these rocks were similarly depleted in many incompatible elements. Further, these rocks are chemically similar to and occupy an analogous early stratigraphic position in the island arc volcanic succession. Although there is no agreement on the significance of this series, its identification elsewhere in the Caribbean is an important step both in interpreting the petrogenesis as well as un-

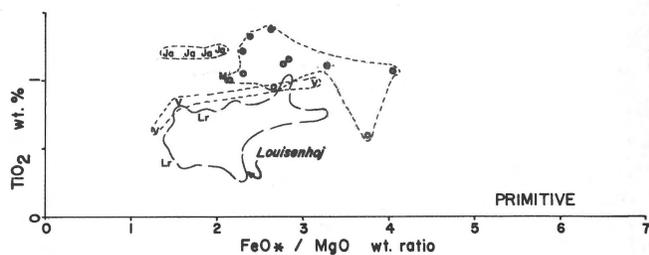


Fig. 6
TiO₂ vs FeO*/MgO ratio, PIA rocks. Field of Louisenhoj Fm. (Virgin Islands) is indicated. Field of Bonaire basalts (circles) unlabeled. Symbols as in Fig. 3; letter symbols as in Fig. 2.

derstanding the tectonic history of the Caribbean during the Jurassic and early Cretaceous.

Bonaire

The Washikemba series has been described by BEETS ET AL. (1977) and by BEETS & MAC GILLAVRY (1977). It contains some Albian (?) fossils and is the oldest rock unit of Bonaire. A group of samples of basaltic rocks and more siliceous porphyrites were analyzed for major elements, as well as a few measurements of Zr and Sr.

The resemblance of these rocks to other PIA series, such as the Louisenhoj of the Virgin Islands, in FMA (Fig. 3), Ti vs. Fe/Mg (Fig. 6), as well as K content (Fig. 4), is striking. Other minor element information was reported by BEUNK & KLAVER (1977) and is consistent with this interpretation. This series is somewhat higher in Ti than the Louisenhoj, but in no way resembles normal CA rocks.

Tobago

The Bacolet breccias are represented by a single analyzed sample, but U, Th, (Fig. 2) and REE (Fig. 7) were measured as well as major elements. Although siliceous rocks were not found, the flat REE pattern appears to place this rock clearly in the PIA group. The U and Th values are consistent, but less definitive because of the overlap of U and Th among MORB, CA and PIA rocks.

Plutonic rocks of Tobago will be discussed below.

Dominican Republic

The Los Ranchos (Early Cretaceous) and Maimón Formations (age unknown) (BOWIN, 1966) are the oldest layered volcanic rocks recognized in the Dominican Republic (aside from the MORB basalts of the Siete Cabezas Formation: DONNELLY & ROGERS, in press). Several samples were analyzed by us, and all appear to belong to the PIA series. The low U and Th (Fig. 2) values and flat REE (Fig. 7) patterns are definitive, as well as the occurrence of highly siliceous rocks.

Sample	Jamaica							Dominican Republic										
	AS 15-1	AS 15-2	AS CH-L	70-116	70-114B	70-115	DR-C	70-125	70-126	70-128	70-129	70-124	70-123	70-130	70-147	70-117	70-148	70-139
SiO ₂	54.5	49.6	53.1	50.4		64.0	71.7	54.3	76.0	68.5	55.0	49.3	47.9	62.1	47.3	46.9	72.4	56.3
TiO ₂	1.22	1.2	1.22	1.24		0.55	0.36	0.74	0.6	0.5	0.74	1.04	0.40	0.60	0.3	1.35	0.31	1.2
Al ₂ O ₃	18.3	14.5	17.3	18.6		16.3	11.9	18.2	11.2	14.6	14.6	19.6	11.7	14.6	14.1	14.0	14.4	12.4
FeO*	6.39	11.3	7.51	9.55		4.58	1.7	8.4	3.7	4.5	6.8	10.7	5.4	7.24	8.1	13.4	2.43	10.5
MgO	4.55	6.9	4.03	4.67		1.82	0.32	4.51	2.0	3.1	6.7	5.08	3.9	7.34	16.2	6.51	0.79	6.6
CaO	8.03	6.9	5.96	6.08		3.88	0.12	9.33	3.3	6.5	9.1	3.65	17.1	0.56	13.6	10.3	4.09	4.3
Na ₂ O	3.86		4.29	4.86		3.29	4.2	1.84	2.6		4.5	5.50	3.8	3.19	0.8	1.05	3.54	5.3
K ₂ O	0.49	0.8	0.57	0.75		3.86	0.89	0.22	1.2	0.4	0.14	0.20	1.6	0.10	0.03	0.22	0.75	0.1
P ₂ O ₅	0.24		0.26	0.28												0.10	0.08	
U	0.4	0.2	low	1.3	0.42	2.0	0.3	0.4		low	0.1		1.1	0.07	low	1.02	0.9	0.2
Th	0.8	0.3	0.6	1.6	1.42	4.1	0.7	0.9		1.7	low		2.0	1.50	low	0.44	2.1	1.2
method	wet	fl	wet	wet		wet	wet	wet	fl	fl	wet	wet	wet	wet	fl	wet	wet	fl

Sample	Aves Ridge Dredge						Desirade						Tobago		
	A 72	A 73	A 78	A 94	1317-5	1317-6	70-62K2	70-62K4	70-62K5	70-62G1	70-62G2	70-62I	70-101	70-102	70-106B
SiO ₂	61.5	65.4	68.2	57.4	69.0	67.2	57.4	75.0	75.0	67.5	73.1	48.1	48.7	46.7	74.2
TiO ₂	0.5	0.5	0.44	0.9	0.36	0.52	0.6	0.2	0.1	0.3	0.3	0.7	0.89	1.0	0.9
Al ₂ O ₃	15.1	14.2	13.0	12.5	15.0	15.6	14.0	13.5	12.7	14.9	14.4	14.6	17.3	14.3	16.9
FeO*	4.6	4.3	4.58	9.1	3.41	3.61	9.2	2.1	2.1	5.7	4.2	12.3	8.18	9.6	7.8
MgO	2.8	2.4	2.84	6.7	1.20	1.53	6.8	0.9	1.6	0.7	1.6	9.0	6.01	9.7	6.0
CaO	3.1	3.0	4.53	5.6	3.69	4.06	4.6	0.9	1.2	2.8	2.5	7.5	11.1	11.4	9.7
Na ₂ O			3.16		3.75	3.79	5.4	7.1	6.7	6.4	5.8	3.8	2.33	2.8	3.4
K ₂ O	7.4	4.8	3.18		2.17	2.20	0.2	0.04	0.05	0.4	0.3	0.3	0.68	1.4	1.1
P ₂ O ₅			0.10		0.18	0.24									
U		1.1	1.3	1.1				0.5	0.08	0.07	0.1	low	0.1	0.5	0.3
Th		4.9	5.2	2.5				0.7	1.4	0.3	low	0.5	0.3	0.5	2.0
method	fl	fl	wet	fl	wet	wet	fl	fl	fl	fl	fl	fl	wet	fl	fl

Sample	Aruba																				
	A17	A102C	A130	A399	A406	A424	A427	A437	A452	A455	A461	68BE 55	68BE 62	68BE 71	68BE 91	68BE 92	75ANT 124	75ANT 132	75AR 18	75AR 19	75AR 31
SiO ₂	50.3	48.8	46.0	46.8	62.6	50.2	51.8	51.4	51.4	54.4	58.9	50.2	51.6	51.9	50.8	49.7	53.4	49.8	68.3	50.2	52.0
TiO ₂	1.13	1.28	1.25	1.27	0.61	0.93	1.18	1.23	1.10	1.12	1.00	0.90	1.14	1.21	1.04	0.87	2.72	1.28	0.78	1.22	1.20
Al ₂ O ₃	12.6	13.8	13.1	14.5	16.2	14.4	12.5	13.4	13.6	12.9	13.4	14.6	14.2	13.5	13.9	14.7	11.5	14.4	14.3	14.3	14.1
FeO*	10.9	12.6	11.3	11.4	6.12	9.89	10.6	10.3	10.4	9.97	8.43	9.27	9.85	11.3	10.2	9.53	16.6	11.8	4.78	10.9	10.4
MgO	7.34	7.25	7.17	8.09	2.71	8.30	7.89	7.52	8.34	6.08	7.26	9.60	7.55	6.44	7.36	8.04	2.56	7.07	1.72	7.33	7.22
CaO	10.6	9.14	9.41	11.2	6.20	10.8	9.01	11.8	9.36	11.8	8.69	11.7	9.68	8.47	11.2	13.2	6.78	11.1	3.76	10.7	11.8
Na ₂ O	2.81	2.96	3.17	2.34	3.77	2.95	3.88	2.91	3.89	2.16	1.53	1.87	3.03	3.71	2.65	1.82	4.59	1.68	5.74	2.92	1.88
K ₂ O	0.22	0.08	0.10	0.33	0.19	0.08	0.12	0.12	0.12	0.06	0.04	0.12	0.08	0.12	0.10	0.08	0.04	0.04	0.08	0.16	0.08
P ₂ O ₅	0.09	0.11	0.10	0.12	0.11	0.06	0.10	0.10	0.09	0.08	0.08	0.07	0.12	0.09	0.10	0.08	0.23	0.11	0.36	0.10	0.10
U																					
Th																					
method	wet	wet	wet	wet	wet	wet	wet	wet	wet	wet	wet	wet	wet	wet	wet	wet	wet	wet	wet	wet	wet

Table I

Major elements, U and Th (in %) for igneous rocks from several localities. The term 'method' refers to the major analysis method: 'wet' means 'rapid methods' (M. Budd, analyst, discussed in Donnelly & Rogers, in press); 'fl' means 'X-ray fluorescence' (J. J. W. Rogers, analyst). The U and Th analyses were done by gamma-ray spectrometry (J. J. W. Rogers, analyst); 'low' means 'a value indistinguishable from zero under the analytical conditions'.

Localities

JAMAICA: AS-15-1, AS-15-2, AS-CH-L: Arthur's Seat volcanics, Central Inlier, vic. Arthur's Seat and Croft's Hill (Robinson); 70-116, Rock River, S.W. of Connors, Central Inlier; 70-114B, Effort Bridge, Central Inlier (above five samples from older volcanic units that have not been correlated); 70-115, pumiceous dacite, Summerfield Fm., near Cushman's River, Central Inlier; DR-C, Devils Race Course volcanics, Benbow Inlier (Robinson).

DOMINICAN REPUBLIC: 70-125, Los Ranchos andesite, 2 km. N.E. of Hatillo; 70-126, Los Ranchos keratophyre, nr. Los Ranchos; 70-128, Los Ranchos keratophyre, nr. Cotui; 70-129, Los Ranchos spilite, 1

km. S.W. of Cotui; 70-124, Maimon Fm., 2 km N.E. of Maimon; 70-123, Peravillo Fm., 1.5 km S.W. of Maimon; 70-130, Tiroo Fm., west of Bonao on road to Constanza; 70-147, norite, nr. Jautia; 70-117, Siete Cabezas Fm., Carretera Duarte, 8 km. S. of Madrigal; 70-148, foliated tonalite, nr. Jautia (above ten samples from area around Bonao described by Bowin (1966)); 70-139, Tiroo equiv.?, 9 km. S. of Constanza; 70-135, basalt, 20 km. S. of Constanza; 70-137, basalt 25 km. S. of Constanza; 70-143, basalt 22.5 km. S. of Constanza; 70-145A, 70-145W, 70-145P: volcanic float from river about 5 km. S. of Constanza; 70-133, rhyolite dome, Loma Cuchilla del Montazo, nr. Constanza; 70-134, dacite, same loc.; 70-136, basalt, 23 km. S. of Constanza; 70-138, basalt, 13 km. S. of Constanza (the above ten samples represent very young volcanics from the Constanza volcanic field).

PEDRO BANK: Pedro, drilled granodiorite from Pedro Banks-1 (Occidental-Signal Cos.) (Lewis).

HAITI: SK-5, Terre Neuve Stock, nr. Gonaives, major elements from Kesler, 1971; SK-6, SK-10, M1(G), M2(LQM), M4(SYN), SK45,

										Pedro Bank	Haiti						
70-137	70-143	70-145A	70-145W	70-145P	70-133	70-134	70-136	70-138		Pedro	SK 5	SK 6	SK 10	M1 (G)	M2 (LOM)	M4 (SYN)	SK 45
49.9	53.9	54.4	58.8	59.1	76.8	70.7	-52.0	50.6	62.4	65.8	63.4	63.6	59.2	62.6	52.3	63.3	
0.74	0.79	0.72	0.94	0.88	0.10	0.47	0.96	0.71	0.6	0.51	0.9	0.9	1.0	0.9	1.6	0.9	
13.5	15.0	13.6	14.5	14.5	10.3	11.8	15.7	13.3	16.1	15.1	13.9	15.6	14.3	14.6	16.2	15.7	
8.74	8.47	7.85	5.11	5.72	2.41	3.92	7.93	7.60	4.6	4.88	6.7	5.0	7.6	6.1	9.9	5.5	
10.1	8.21	8.82	5.90	2.90	0.28	1.26	4.62	8.24	4.7	1.68	4.2	4.3	3.4	2.6	4.6	3.2	
9.41	9.07	8.56	7.30	5.10	0.14	1.10	8.08	8.72	4.3	3.29	5.7	5.4	5.5	5.0	8.3	4.8	
2.54	2.80	2.80	2.88	3.36	0.24	4.24	3.54	2.85	3.4	3.33	2.9	3.6	3.8	3.7	3.1	3.4	
2.20	2.56	2.18	4.70	4.32	7.92	1.49	2.69	1.81	3.3	2.75	2.0	3.2	2.8	3.4	1.2	3.4	
0.22	0.22	0.24		0.47				0.25		0.15							
1.0	0.9	0.6		2.4	1.7	0.7	2.1	1.8	2.5	1.9		2.1	1.4	1.7	1.4	2.0	
3.8	3.5	3.7		8.1	2.5	3.3	7.6	6.5	5.8	6.8		6.4	6.0	4.3	2.5	6.9	
wet	wet	wet	wet	wet	wet	wet	wet	wet	fl	Kesler 1971	fl	fl	Kesler 1968	Kesler 1968	fl	fl	

Testigos	Gran Roque		La Blanquilla		Margarita	Los Frailes		Tiara			Paraguana Peninsula		
	CS-6	CS-7	CS-8	CS-9	Marg	DFM 1005D	DFM 1001	CS-49	CS-48	CS-50	FA-6332	FA-527A	FA-527B
	67.7	63.8	62.9	69.0	72.7	55.1	53.9	44.3	48.6	54.2	47.4	47.9	47.9
	0.6	0.7	0.62	0.32	0.32	1.38	1.0	1.39	0.6	1.3	0.8	1.37	1.1
	12.4	14.3	16.9	17.3	13.6	17.8	13.8	14.0	12.4	10.7	15.4	15.5	14.9
	6.9	6.4	6.30	1.70	1.90	7.74	10.3	8.17	6.5	6.5	6.3	9.80	8.6
	3.4	6.4	2.96	0.93	1.60	1.65	4.5	6.68	13.2	9.6	16.0	8.28	9.7
	5.2	5.0	6.27	3.82	2.89	6.81	7.1	17.1	15.5	14.1	13.4	11.35	11.8
			3.12	5.28	4.76	3.86		0.16				2.19	
	1.6	1.6	1.43	1.26	0.80	1.46	1.3	0.08		0.1	0.1	0.08	0.2
			0.08	0.09	0.19	0.53		0.17					
	0.9	0.7	4.6	2.2		0.7	0.6		0.06		0.07	low	0.1
	6.7	3.1	1.0	6.3		1.5	1.4		low		0.06	0.4	low
	fl	fl	wet	wet	wet	wet	fl	wet	fl	fl	fl	wet	fl

Bonaire																		
BE3BO	BE8BO	BE33BO	BE79BO	BE103 BO	BE180 BO	BE194 BO	BE218 BO	BE227 BO	75ANT 30	75ANT 73	75BO37	75BO43	75BO 230	75BO 231	75BO 303	75BO 329	75BO 335	75BO 347
53.6	53.3	54.2	65.4	63.9	72.2	71.7	57.3	54.2	69.2	71.7	50.4	49.4	67.8	61.6	53.6	73.7	49.7	59.3
1.07	1.21	0.95	0.63	0.73	0.69	1.38	1.15	0.51	0.66	1.12	1.14	0.74	0.60	1.33	0.28	1.05	1.00	
14.3	15.0	16.6	13.9	14.3	12.3	13.9	15.2	14.8	13.1	14.0	13.8	13.4	13.2	14.6	14.1	10.6	14.7	16.2
11.3	12.0	8.03	3.73	4.63	2.11	3.21	8.98	11.1	2.99	10.6	9.32	3.47	7.60	7.60	8.25	1.32	9.15	8.38
2.79	5.20	3.05	1.85	1.79	0.71	0.59	3.47	3.87	0.46	0.71	3.26	3.35	0.28	2.03	3.50	0.28	3.96	3.91
5.97	0.48	1.97	1.07	1.88	0.91	0.30	2.63	4.62	0.58	0.84	9.62	9.95	0.79	3.47	7.36	0.87	10.1	1.32
4.34	4.34	6.35	5.54	5.23	6.22	5.76	5.25	4.55	6.10	6.00	4.20	4.41	6.28	5.16	4.73	4.56	4.37	5.25
0.54	0.18	1.15	2.34	1.77	1.72	1.74	1.42	1.94	2.22	2.36	0.16	0.04	1.51	2.18	1.49	1.12	0.54	1.24
0.21	0.18	0.17	0.37	0.32	0.47	0.09	0.26	0.25	0.16	0.32	0.20	0.17	0.25	0.25	0.26	0.09	0.15	0.23
wet	wet	wet	wet	wet	wet	wet	wet	wet	wet	wet	wet	wet	wet	wet	wet	wet	wet	wet

same loc. (Kesler). Major elements of M1(G) and M2(LQM) from Kesler, 1968;

AVES RIDGE: A72, A 73, A78, from dredge 12 (15°14' N, 65°58' W) (Nagle) A 94, dredge † 13, (12° 17'N; 63° 32' W) (Nagle) (the above four samples are of dredged anesites from the aves Ridge.); 1317-5, 1317-6, 1318-1-D; dredge 1317, 1318 (12°20' N, 63°30' W; 12°19' N, 63°27' W) (Fox) (the above three samples are of granodiorite (two) and cumulate gabbro (one), for which the major element analysis is given in Donnelly *et al*, 1973).

LA DESIRADE: 70-62K2, 70-62K4, 70-62K5, 70-62G1, 70-62G2, 70-62I: all from older complex of western end of island, Porte d'Enfer (the first three are keratophyres, the next two trondjemite, and the last a mafic dike).

TOBAGO: 70-101, Bacolet Fm. breccia, Hillsborough Bay; 70-102, diorite from Carapuse Bay; 70-106B, diorite from Arnos Vale Bay.

LOS TESTIGOS: CS-3, pegmatitic diabase, Testigo Grande.

GRAN ROQUE: CS-6, CS-7, quartz diorite.

LA BLANQUILLA: CS-8, tonalite; CS-9, trondjemite (all Cs samples

from Schubert).

MARGARITA: Matasiete trondjemite.

LOS FRAILES: DFM-1005D, DFM-1001, diabase and diorite from Fraile Mayor (Moticska).

VENEZUELA: CS-49, CS-48, CS-50, Tiara volcanics, all from 3 km ENE of Tiara, Aragua (Schubert); FA-6332, FA-527A, FA-527B: Paraguana Peninsula, Cerro Siraba (one) and Cerro Santa Ana (two) gabbros (Martín-Bellizia).

ARUBA: A17, A102C, A130, A399, A406, A424, A427, A437, A452, A455, A461, basalts from the basal complex, except for A399 and A406, which are diabases (MacDonald); 68BE55, 68BE62, 68BE71; 68BE91, 68BE92, 75ANT124, 75ANT132, 75AR19, 75AR31 are basalts, 75AR18 is an intermediate rock (Beets).

BONAIRE: BE3BO, BE8BO, BE33BO, BE218BO, BE227BO, 75BO37, 75BO43, 75BO231, 75BO303, 75BO335 (all basalts), BE2BO, BE79BO, BE103BO, BE180BO, BE194BO, 75BO230, 75BO329, 75BO347, 75ANT30, 75ANT73 (all porphyrites) Washikemba Fm. (Beets).

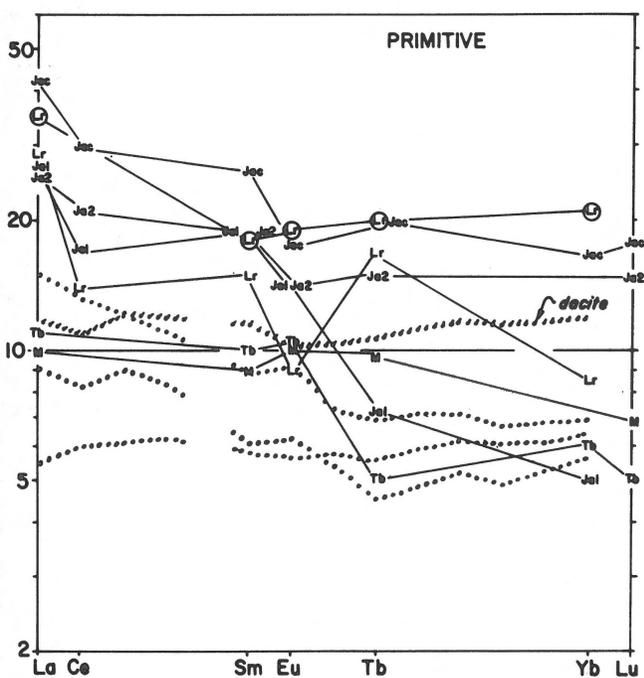


Fig. 7
REE of PIA series, chondrite normalized. Patterns for one dacite and three andesites from the Lousenhoj Fm. (Virgin Islands) (Donnelly & Rogers, in press) are shown. Letter symbols as in Fig. 2.

The Peravillo breccia, a younger (post-Maimón) pyroxene andesite, is chemically ambiguous. The single analyzed sample has higher U and Th values than are typical for the PIA series, and it could belong to the CA group.

The Tireo volcanic breccias (late Cretaceous), which occur on the west side of the Hatillo Thrust, and are thus non-correlative with the above-listed rocks series, are represented here by two analyses, including U and Th, and one REE analysis. The U and Th values are ambiguous, but the REE pattern of a Tireo sample shows the characteristic light REE (Fig. 8) enrichment associated with the CA series, and we tentatively assign these rocks to this series.

Jamaica

The volcanic stratigraphy of Jamaica has been described recently by ROOBOL (1972). Samples from the Benbow Inlier (Devil's Race Course volcanics) and the Central Inlier (Arthur's Seat volcanics and possibly correlative rocks at Connors) were analyzed for major elements, U, Th, and REE. The single specimen from the Devil's Race Course volcanics is siliceous, but with the characteristic low U, Th, (Fig. 2) and K of the PIA series. The Arthur's Seat and Connors specimens have U and Th values too low for the CA series, and REE patterns (Fig. 7) closer to the PIA than to the other series. However, one of the three samples has lower values of Tb and Yb and is not typical of PIA rocks known to us. The as-

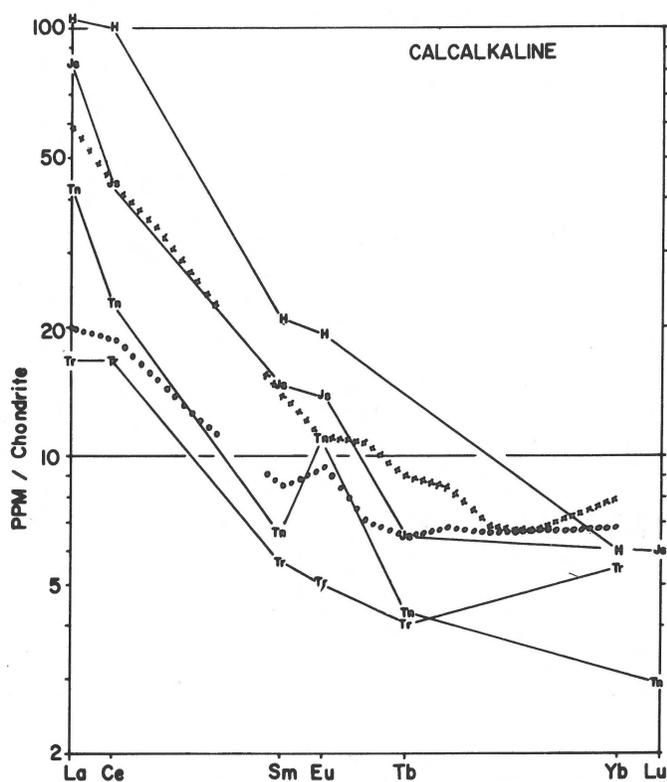


Fig. 8
REE of calcalkaline rocks, chondrite normalized. Dacite from St. Lucia (x's) and a basalt from Montserrat (dots) are shown (Donnelly & Rogers, in press). Letter symbols as in Fig. 2.

signment of these rocks to the PIA series is not completely clear but appears to be indicated by the data at hand. The close similarity between the Arthur's Seat and Connors specimens should be noted.

In clear contrast to these rocks, is a sample from the Maastichtian Summerfield Formation. The REE pattern (Fig. 8), U and Th (Fig. 9) values, and major element chemistry is completely typical for the CA series.

Venezuela

We have done no original analytical work on the Villa de Cura volcanics, but inspection of major element analyses reported by SHAGAM (1960) suggest, in the low Ti values of the basic rocks (Fig. 6) and the occurrence of low K, siliceous rocks, that these rocks will ultimately be assigned to the PIA series. An approximate correlation with the Washikemba Formation is suggested but will require substantiation.

La Désirade

Several siliceous and one mafic sample were included in our survey. In addition to major element data, U and Th values (Fig. 2) are available. REE were reported by JOHNSTON &

Plutonics of South American Continental Borderland

sample	1317-5	1317-6	1318 1-D	CS-8	CS-9	Marg	P.I. & V.I. plut.-range
Zr	143	122	20	58	82	122	9-160
Cr	4	2	10	12	4	32	3-198
Ni	6	4	22	10	6	34	6-40
Co	—	94	36	66	174	165	4-41
V	83	62	400	166	49	42	45-320
Cu	10	5	61	169	14	25	7-160
Sr	450	450	620	180	860	540	60-570
Ba	1020	790	125			105	55-1040
Rb						6.5	2-63

Table II

Minor elements in ppm.

Top: plutonic rocks from the South American continental borderland, compared with 14 Puerto Rico-Virgin Islands plutonic samples. Transition metals and Ba by emission spectroscopy (T. Donnelly, analyst); Zr, Sr, and Rb by X-ray fluorescence (B. Peasley, analyst).

Middle: Zr and Sr from Aruba and Bonaire older volcanic rocks, X-ray fluorescence (T. Donnelly, analyst).

Bottom: rare earth elements from igneous rocks of Jamaica, Tobago, Haiti, and the Dominican Republic, neutron activation analysis (J. J. W. Rogers, analyst).

sample	Aruba					Bonaire					
	A102C	A399	68BE55	68BE62	75ANTI32	75ANT30	75BO37	75BO230	75BO231	75BO329	75BO335
Zr	70	40	30	30	45	90	60	80	75	85	40
Sr	85	155	80	75	94	20	130	45	80	150	440

sample	Jamaica				Tobago	Haiti	Dominican Republic				
	AS-CH L	AS-15 1	70-115	70-116	70-101	M2 (LOM)	70-124	70-125	70-126	70-130	70-148
La	7.6	8.1	24.9	12.8	3.4	32.4	3.0	8.6	10.5	5.1	12.5
Ce	18	14	37	25		83.9		11.9		14.3	19
Sm 3.8	3.8	3.1	5.4	2.0	4.5	1.9	3.1	3.8	1.2	1.4	
Eu	1.05	1.01	1.0	1.3	.77	1.4	.76	.66	1.4	.37	.79
Tb	.75	.35	.32	.96	.24		.48	.84	1.0	.20	.21
Yb		1.0		3.3	1.2	1.2		1.7	4.2	1.1	
Lu	.5		.2	.6	.17		.23			.23	.1

SCHILLING (1974) but have not been subsequently published. The resemblance of these rocks to the Water Island Formation of the Virgin Islands is striking, except that the latter include no hypabyssal plutonic rocks. These rocks are assigned without hesitation to the PIA series.

Summary

The PIA series is widespread in the Caribbean and is prevalent among Jurassic to Middle Cretaceous rocks (where these can be dated). It is chemically somewhat heterogeneous, especially with regard to Ti in the mafic rocks and in the REE patterns. Further studies may well show regional differences in minor element depletion, in which case the Puerto Rico-Virgin Islands (and possibly Désirade) rocks will probably be the most depleted.

The tectonic implications of the PIA series are not clear. Although occurring early in the island-arc evolution in the Caribbean and elsewhere, they represent an as yet-unidentified tectonic stage in the evolution of the island-arc. In some instances, they represent abyssal (pre-island-arc platform) eruption followed by emergence (DONNELLY, 1972), and in other examples they represent emergence without the demonstration of early very deep water eruption (GILL, 1970). Their lead isotopes especially, and their minor elements generally, separate them from the later calcalkaline series and

show that different source materials were being melted. Except that these materials do not seem to include continental materials, and do appear to have been intrinsically hydrated, little can be said about them. The later calcalkaline melts could well include contamination by either crustal materials or oceanic sediments and seem to be related clearly to the mature Benioff zone.

In the southern Caribbean, we envision the following sequence of events:

(1) eruption of MORB within the basin accompanying an early-middle Cretaceous regional extensional event (but not spreading at a well-defined ridge).

(2) (perhaps contemporaneous with (1): an island arc developing on oceanic crust immediately north of the South American continental shelf.

(3) Tectonic obduction of the basinal crust on to the South American continental margin, perhaps accompanied by a thermal event such that much of the impetus for the slide was gravity. The early island-arc materials might have moved a short distance or could remain as autochthonous masses on Bonaire, Tobago, etc.

(4) Intrusion by extensive Late Cretaceous calcalkaline plutons especially east of Bonaire but also including small bodies in the Netherlands Antilles. This event could be related to the putative thermal event responsible for some of the Villa de Cura sliding.

HIGH POTASSIUM VOLCANIC ROCKS FROM THE DOMINICAN REPUBLIC

A very young volcanic field was found near Constanza, in the Dominican Republic during a geological reconnaissance in 1970. Rocks from this series were analyzed for major elements, U and Th (Fig. 9), and range from olivine basalts to rhyolites. Three analyses of rocks apparently from near this area were reported by WEYL (1966) and are included here. The rocks appear to be alkalic, though less so than those reported from further west in the Dominican Republic (MACDONALD & MELSON, 1969) AND Haiti (WOODRING ET AL., 1924).

The FMA relationships (Fig. 10) show that these rocks are a very young analogue of the high-K (shoshonite) rocks reported from Puerto Rico (JOLLY, 1970, 1971) and elsewhere. These rocks are notable elsewhere for a lack of coherence between K and Si, which is not the case in the present samples (Fig. 4). However, the high Mg, and modal olivine, even in rocks with andesitic silica values, are characteristic of this and other high-K series. The petrogenesis of rocks of this group is unclear. Elsewhere they occur among the younger volcanic rocks, but the Puerto Rican examples are relatively old. The relationship between geographic position in the island-arc and K content is generally not clear in this group, but the above-cited examples from further west in the Dominican Republic and Haiti show increasing K/Si ratios to the west. The occurrence of these rocks on a large island is consistent with occurrences of similar rocks in Viti Levu (GILL, 1970) and New Guinea (SMITH, 1972).

SUMMARY

A survey of igneous rocks associations around the Caribbean leads to several interesting conclusions. The finding of early PIA series followed by CA rocks in the Puerto Rico-Virgin Islands area is paralleled in Jamaica, the Dominican Republic, the southern islands of the Caribbean (where the later CA is dominantly plutonic), Désirade, and possibly, Tobago. The identification as MORB of a widespread suite of basaltic rocks distributed in northern Venezuela, Curaçao, and, Aruba, raises an important question as to the origin of these putative oceanic rocks in a continental margin environment. The interpretation of the Villa de Cura volcanic series as a major allochthonous slide raises the possibility that all the occurrences of MORB are similarly allochthonous. The gravity survey results from the Paraguana occurrence (MARTÍN-BELLIZIA & AROZENA, 1972) show that the basaltic mass lacks roots, and the data from Curaçao (SILVER ET AL., 1975) allow a similar interpretation. Further work to elucidate the relationships between MORB and PIA rocks in the southern Caribbean would appear to be one of the most important steps to unravel the complex tectonic history of this area. We hope that the results will stimulate further geochemical-tectonic investigations in these critical areas.

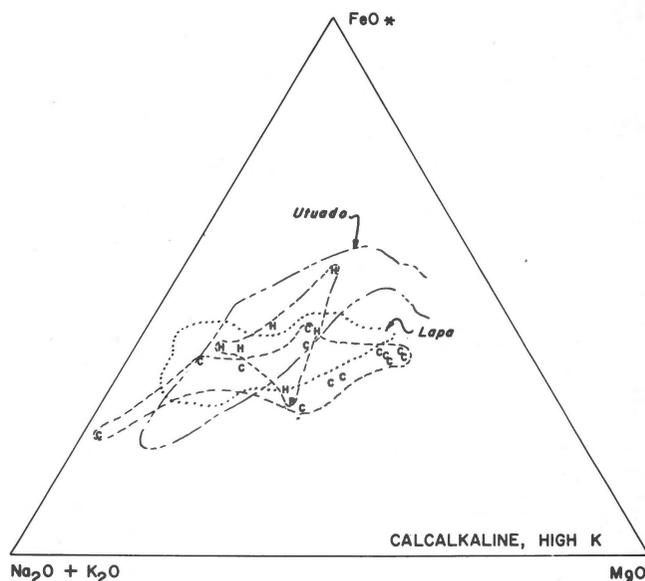


Fig. 10
FMA diagram for calcalkaline series. Fields of the Utuado Pluton (Puerto Rico) and the Lapa volcanics (Puerto Rico) are indicated. Letter symbols as in Fig. 2.

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