New plate tectonic model of the Caribbean: Implications from a geochemical reconnaissance of Cuban Mesozoic volcanic rocks

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ABSTRACT

Accreted terranes, comprising a wide variety of Jurassic and Cretaceous igneous and sedimentary rocks, are an important and conspicuous feature of Cuban geology. Although the Mesozoic igneous rocks are generally poorly exposed and badly altered, we have collected and geochemically analyzed 25 samples that place new constraints on plate tectonic models of the Caribbean region. From our recognizance sampling, six main lava types have been identified within the Mesozoic igneous rocks of Cuba: rift basalts, oceanic tholeiites, backarc basin lavas, boninites, island arc tholeiites (IAT), and calc-alkaline lavas. We suggest that the rift-related basalts may have formed during the development of the proto-Caribbean, as the Yucatan block rifted away from northern South America in Jurassic–Early Cretaceous time. The Early Cretaceous oceanic tholeiites have flat rare earth element patterns, and are compositionally similar to Pacific mantle plume–derived oceanic plateaus of similar age. The Early Cretaceous arc-related rocks are either backarc basalts, boninites, or relatively trace element–depleted IAT lavas. A limited amount of geochemical and field evidence hints that two parallel arc systems existed in the western proto-Caribbean area in Early Cretaceous time. This leads us to speculate that in the proto-Caribbean at this time there was a western arc with a northeast-dipping subduction zone erupting IAT lavas (with Farallon plate being consumed), and a more eastern boninitic arc with a south-west-dipping subduction zone (with proto-Caribbean plate being consumed). This latter arc was relatively short lived and after being aborted was mostly eroded away. The Cretaceous primitive (IAT) arc survived and, later in Cretaceous time, as this arc system moved into the widening gap between North and South Americas, calc-alkaline lavas began to be erupted. The evidence suggests that the change from IAT to calc-alkaline lavas was gradual and not abrupt. These new data, although limited, provide geochemical constraints on the tectonic development of the northern part of the Caribbean plate. In consequence, we present a new plate tectonic model for this area of the Caribbean.

INTRODUCTION

Over the past 40 yr extensive geological mapping programs have been undertaken in Cuba. To help improve our understanding of the significance of Cuban magmatic suites in a Caribbean context, detailed geochemical data are required for the Jurassic-Cretaceous mafic igneous rocks that compose a substantial proportion of the island. These geochemical characteristics could help to determine the original plate tectonic setting of these Cuban igneous rocks, and help reconstruct the pieces in the plate tectonic jigsaw that controlled the evolution of the Caribbean plate and its interaction with the surrounding plates. The Cuban Mesozoic volcanic rocks are poorly exposed and badly altered; nevertheless we have been able to collect and analyze 25 critical samples. This study represents a first attempt to apply modern geochemical techniques to Cuban Mesozoic igneous rocks. Although our sample base is too limited to draw detailed petrogenetic conclusions, we have been able to use the geochemical data to place important new constraints on the tectonic development of the northern Caribbean. Moreover, we can use these new Cuban geochemical data, along with published data from other Cretaceous Caribbean igneous rocks, as a framework on which to construct an integrated (tectonic and geochemical) plate tectonic model of the Caribbean.

BACKGROUND

Although earlier workers suggested that the Caribbean plate formed in situ, with only minimal movement after formation (Schubert, 1935; Meyerhoff and Meyerhoff, 1972), most workers now appear to be in broad agreement that the Caribbean plate was formed in the Pacific and was transported into its present location by significant eastward plate movements (Burke et al., 1984; Burke, 1988; Pindell and Barrett, 1990; Pindell, 1990; Montgomery et al., 1994). Nevertheless, within this consensus there is some debate as to the nature and origin of the components of the Caribbean plate and the timing and extent of movements (e.g., Burke, 1988; Donnelly, 1989; Pindell and Barrett, 1990; Pindell, 1994; Iturralde-Vinent, 1994, 1997).

Within the past 25 yr there has been an increasing realization that the Caribbean plate represents an area of overthickened oceanic crust ~8–20 km (Edgar et al., 1971; Case et al., 1990). This thickened crust was drilled by Deep Sea Drilling Project Leg 15, and Donnelly (1973) proposed that a large part of the Caribbean plate was formed during an oceanic flood basalt event in Late Cretaceous time (Cenomanian-Campanian).

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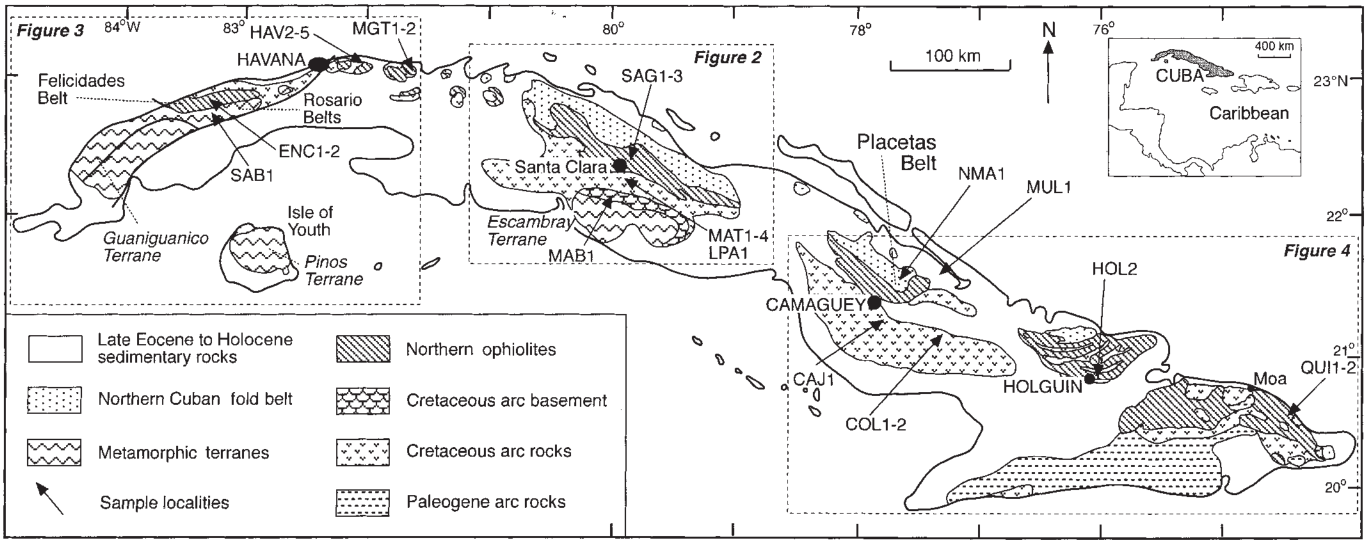

Figure 1. Map of Cuba showing the main lithological units discussed in the text. Also shown are approximate sample locations; Table 1 and Figs. 2–4 give more detailed locations (after Iturralde-Vinent, 1994).

Since 1973, remnants of this igneous province have been identified in accreted and obducted terranes, around the margins of the Caribbean plate (Beets et al., 1984; Donnelly et al., 1990), and in northwestern South America (Kerr et al., 1997b). These igneous rocks are now widely recognized as the remnants of a major oceanic plateau (cf. Burke et al., 1978; Duncan and Hargraves, 1984; Donnelly et al., 1990; Kerr et al., 1997b) that formed as the result of the upward rise and decompression melting of a large mantle plume head. Recent $^{40}Ar/^{39}Ar$ step heating of these plateau basalts and picrites (Kerr et al., 1997a; Sinton et al., 1997) showed that the bulk of magmatism associated with the province formed in a relatively short time period between 91 and 87 Ma. Younger (72–78 Ma) and older (Early Cretaceous) volcanic plateau-building episodes, however, have also been identified within the province (Kerr et al., 1997a; Sinton et al., 1997; Lapierre et al., 1997). Thus, the geological history of the Caribbean region and the borderlands of northwestern South America has been strongly influenced by the accretion of an oceanic plateau, with at least two eruptive phases.

At least two sequences of Cretaceous arc rocks (island arc tholeiites and calc-alkaline rocks) are also found around the margins of the Caribbean region (Donnelly et al., 1990; Dengo and Case 1990; Kerr et al., 1997b), which both predate and postdate the main phases of plateau formation. Despite this, these arc rocks have not yet been found stratigraphically interleaved with the plateau lavas (Kerr et al., 1997b). These arc rocks appear to have been accreted on to the margins of the Caribbean plateau during obduction, possibly in Late Cretaceous and early Tertiary time (Kerr et al., 1997b).

CUBAN GEOLOGIC SETTING

The pre-late Eocene geology of Cuba principally consists of a series of folded accreted terranes of continental and oceanic affinity that strike approximately parallel to the axis of the island (Fig. 1). See Iturralde-Vinent (1994, 1996a, 1997) for recent reviews.

Northern Cuban Fold Belt

The Northern Cuban fold belt is a set of northward thrust units developed along the northern half of the island of Cuba, as well as the shelf and northern keys. This unit has been divided into the Cayo Coco, Remedios, Camajuani, and Placetas belts and the Asuncion massif (Khudoley, 1967; Meyerhoff and Hatten, 1974; Iturralde-Vinent, 1994, 1996a). To the south, at its base, this fold belt is in thrusted contact with the northern ophiolite melange (or subduction-accretion complex) and the Cretaceous volcanic arc suite (Fig. 2). This fold belt consists of strongly deformed predominantly sedimentary rocks of Jurassic-Cretaceous age deposited on a passive margin, and a Paleocene to Eocene foreland basin. In general, the northernmost units are typical of the Bahamas platform (Cayo Coco and Remedios belts), whereas those to the south represent the continental slope (Camajuaní belt) and the old Caribbean basin sections (Placetas belt; Figs. 2 and 3). Detailed descriptions of these sections were given in Meyerhoff and Hatten (1974), Pardo (1975), and Iturralde-Vinent (1994, 1997).

Within the Placetas belt, near Camagüey, Tithonian pillow basalts, hyaloclastites, and calcareous tuffites (~60 m thick) (Nueva Maria Formation; Iturralde and Mari Morales, 1988) crop out at the base of a sedimentary section comprising limestone, shales, and cherts of late Tithonian–Maastrichtian age (Fig. 3). The mafic volcanic rocks have been interpreted as having formed in a continental margin setting as a result of the rifting of thin crust (Iturralde-Vinent, 1988). One sample was collected from this locality (NMA1, Table 1), but it was too altered for geochemical analysis.

Allochthonous Terranes

Three structurally and lithologically complex allochthonous terranes (the Guaniguanico, Pinos, and Escambray) are present in south-central and western Cuba (Figs. 1, 2, and 4). All three terranes expose Jurassic-Cretaceous sedimentary sections of continental margin type, along with some ophiolites and Cretaceous volcanic arc suites (Somin and Millán, 1981). In Guaniguanico, however, Paleocene to lower Eocene foreland sediments (Bralower and Iturralde-Vinent, 1997) can also be found. These terranes are strongly deformed and display varying degrees of metamorphism. There is strong evidence that the Guaniguanico, Pinos, and Escambray terranes were detached from their original position along the eastern margin of the Maya block (Yucatan platform) (Iturralde-Vinent,

1994; Hutson et al., 1998). These terranes are preserved as tectonic windows that crop out within the Cretaceous arc rocks (Figs. 2 and 4). The tectonic emplacement of these terranes below the Cretaceous arc suites appears to have been completed in Late Cretaceous time for the Pinos and Escambray terranes, and in middle Eocene time for the Guaniguanico terrane (Somin and Millán, 1981; Iturralde-Vinent, 1994, 1996a, 1997; Bralower and Iturralde-Vinent, 1998). Detailed descriptions of these terranes can be found in Iturralde-Vinent (1994, 1996a, 1997).

Mafic igneous rocks of Early-Middle Jurassic through Early Cretaceous age are found in all these terranes. They occur as interbedded flows, sills, or dikes within the Jurassic-Cretaceous sedimentary sections (Iturralde-Vinent, 1988, 1996c). In the Pinos and Escambray terranes these rocks are strongly metamorphosed, but they are much less metamorphosed in the Guaniguanico terrane. The samples in this study were collected within the latter terrane, and so a brief description of the geologic setting follows.

The Guaniguanico terrane of western Cuba (Fig. 4) consists of a stack of several northwestward-trending thrust belts; those thrust belts higher in the tectonic pile are more allochthonous (Iturralde-Vinent, 1994). The structurally lower units are named, from bottom to top, Los Organos and Rosario belts (subdivided into Rosario South, Rosario North and Quiñones), and chiefly consist of sedimentary rocks of possible Early Jurassic to Late Cretaceous age (Pszczolkowski, 1978). The structurally higher belts consist of serpentinites, gabbros, and Cretaceous igneous and sedimentary rocks of the Felicidades belt (Fig. 4; Iturralde-Vinent, 1994).

Two mafic units have been sampled from the Guaniguanico terrane; the El Sábalo Formation (SAB 1–2) in the South Rosario belt, and the Encrucijada Formation (ENC 1–2) in the Felicidades belt (Fig. 4). The El Sábalo Formation consists of a ~400-m-thick sequence of pillow basalts and hyaloclastites with thin limestone intercalations, paleontologically dated as late Oxfordian–early Kimmeridgian age. On the basis of this stratigraphic position, Iturralde-Vinent (1988, 1996c) proposed that these basalts were formed in a continental rifting setting during the early opening of the Caribbean seaway.

The Aptian-Albian Encrucijada Formation (100–200 m thick) consists of a sequence of pillow basalts and hyaloclastites with interbedded sediments. These are overlain by the volcanic-sedimentary Cenomanian-Turonian Quiñones Formation (nearly 600 m thick). The section is usually strongly deformed, and its base has not been found, although it is in tectonic contact with thin strips of fractured serpentinites and Mesozoic gabbros (Fig. 4; Iturralde-Vinent,

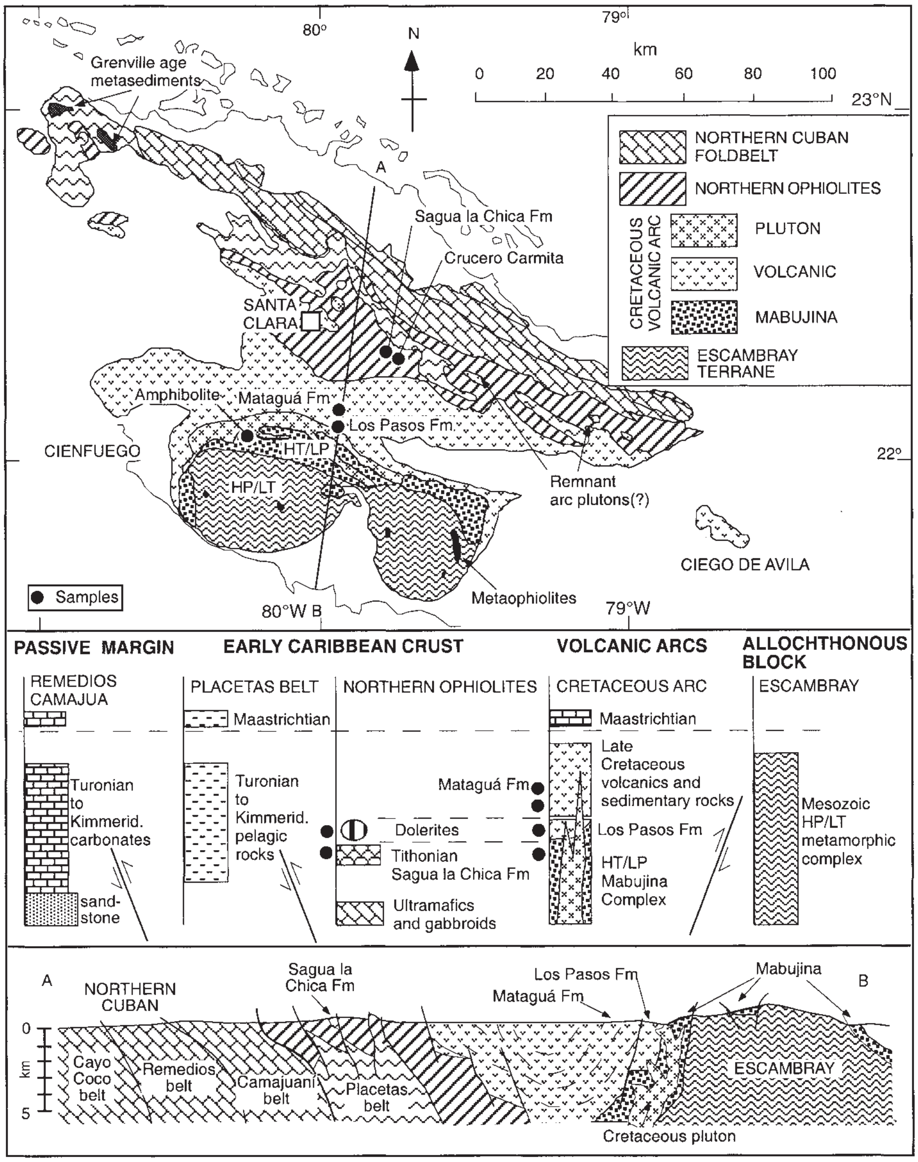

Figure 2. Sample map for central Cuba, showing geology, cross sections, and generalized stratigraphic sections. HT/LP—high temperature, low pressure; HP/LT—high pressure, low temperature.

1996b). This section of igneous and sedimentary rocks (Felicidades belt) has been interpreted as a fragment of the Caribbean ocean crust within a backarc–marginal sea setting (Iturralde-Vinent, 1988, 1994; Cruz and Simón, 1992; Cruz, 1998). Rocks belonging to the northern ophiolite melange and the Cretaceous volcanic arc (the Bahía Honda-Matanzas allochthon; Fig. 4) are found in thrusted contact with the Guaniguanico terrane. Within the Cretaceous volcanic arc in the Bahía Honda-Matanzas area is suite of rocks lithologically and geochemically very similar to the Encrucijada Formation. The Bahía Honda–Matanzas Cretaceous volcanic section has also been interpreted as a backarc–marginal sea (Cruz and Simón, 1992; Cruz, 1998; Iturralde-Vinent, 1996d, 1996e).

Tectonic Units of Oceanic Affinity

Units of oceanic affinity are represented by the Northern ophiolitic melange and the Cretaceous island arc (sensu Iturralde-Vinent, 1994). Previously workers have grouped these units into several formations, or have collectively referred to these belts as the Zaza tectonic unit or terrane. The Paleogene-Eocene island arc is found only in eastern Cuba (Fig. 1). More detailed descriptions

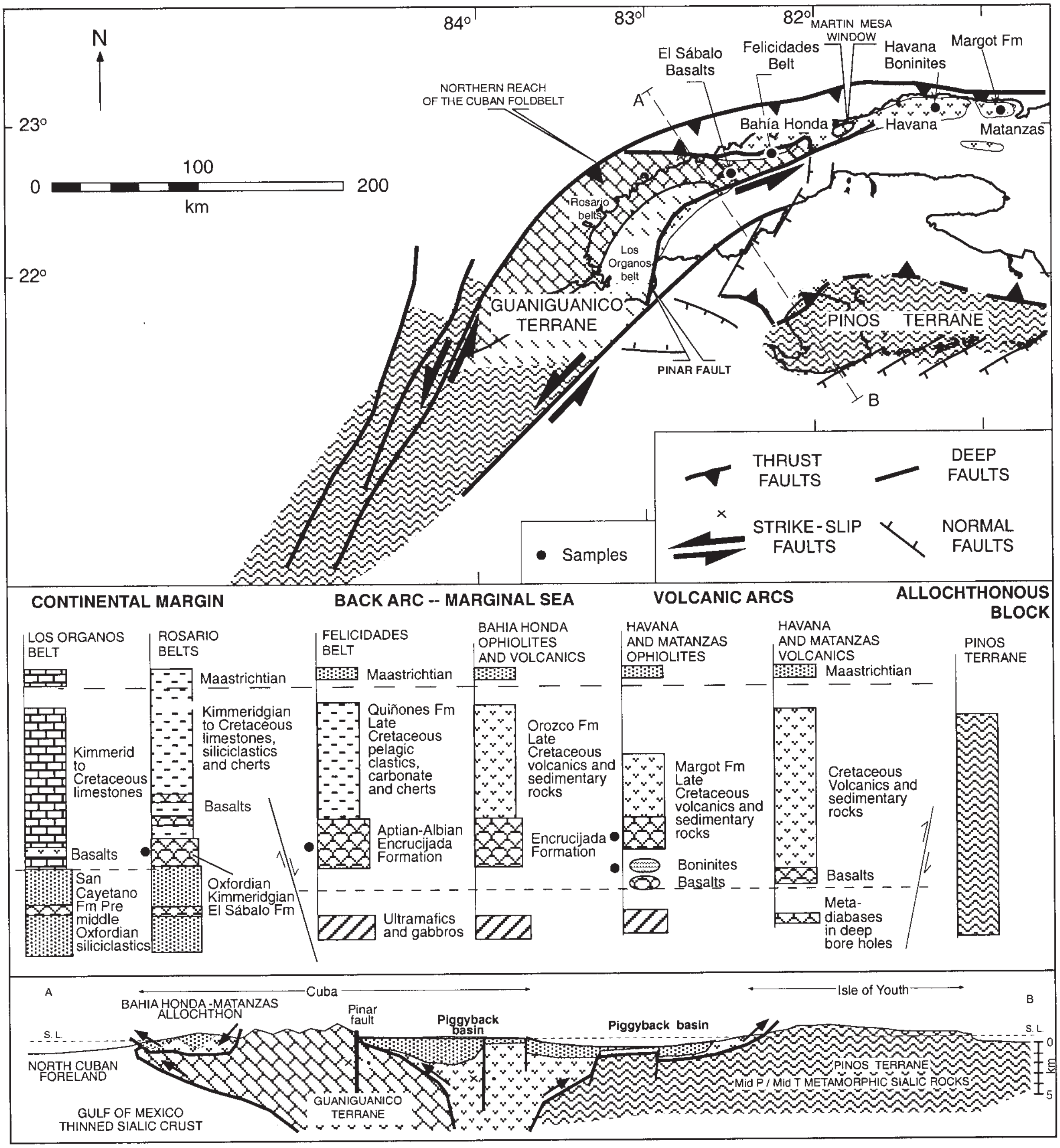

Figure 3. Sample map for western Cuba, showing geology, cross section, and generalized stratigraphic sections.

of these units can be found in Pushcharovsky et al. (1988) and Iturralde-Vinent (1994, 1996b).

Northern Ophiolite Melange. This melange occurs in the northern half of Cuba, as an allochthonous body that has been thrust north and northwestward onto the foreland basins of the Guaniguanico terrane and the Northern Cuban fold belt (Fig. 1). Usually they are strongly deformed, partially metamorphosed, and occur amalgamated both with nappes of the foreland basement and with segments of the overlying Cretaceous arc rocks. The bulk of the northern ophiolite melange is composed of ultramafic tectonites with layered (cumulate) gabbros, which yield Mesozoic K-Ar dates (Iturralde-Vinent et al., 1996). These rocks are usually intruded by isolated dikes of ultramafic and mafic composition, yielding Mesozoic K-Ar ages (Iturralde-Vinent et al., 1996). Mesozoic volcanic and sedimentary blocks are found tectonically embedded within the melange of deformed serpentinite and gabbros. These blocks vary from isolated cobble and boulder sized to bodies as much as a few hundred meters thick, and are composed of basalts, hyaloclastites, cherts, limestones, shales, and other rocks (Iturralde-Vinent, 1994, 1996b). These mafic igneous and sedimentary sections have been interpreted as sequences formed within a marginal sea–backarc environment (Iturralde-Vinent, 1989, 1994, 1996b), or within a suprasubduction forearc setting (Andó et al., 1996). Geochemically, the basalts are oceanic tholeiites (Fonseca et al., 1990). Inclusions of high-pressure

TABLE 1. LOCATION AND BRIEF GEOLOGICAL INFORMATION ABOUT THE SAMPLED SITES

Sample	Rock type	Geological setting	Locality	References
SAB-1	Basalt of El Sábalo Formation	Continental margin rift tholeiites of Guaniguanico terrane	Locality Mango Bonito, along the road Carretera de Montaña, 1.2 km west of the intersection with the road from Bahía Honda to San Cristobal, Sierra del Rosario, Pinar del Río Province	Pszczolkowski, 1978; Iturralde-Vinent, 1988, 1996c
ENC1	Basalts of Encrucijada Formation	Oceanic tholeiites of the northern ophiolites	West of Bahía Honda, outcrop on the road heading South to Cacarajícara, 1 km south of the intersection with the road to La Mulata, Pinar del Río Province	Zelepuguin et al., 1982; Iturralde-Vinent, 1988, 1996b, 1996c
ENC2	Basalts of Encrucijada Formation	Oceanic tholeiites of the northern ophiolites	West of Bahía Honda, outcrops in the river Las Pozas, 200 m northwest of the first bridge on the road heading south to Cacarajícara, Pinar del Río Province	Zelepuguin et al., 1982; Iturralde-Vinent, 1988, 1996b, 1996c
HAV2	Dolerites	Blocks in the northern ophiolites	Southwest of the town of Campo Florido, outcrops along Central railroad near the small village of San Miguel, La Havana Province	Albear and Iturralde-Vinent, 1985; Fonseca et al., 1989
HAV3	Basalts	Oceanic tholeiites of the northern ophiolites	Southwest of the town of Campo Florido, outcrops along Central railroad near the small village of San Miguel, La Havana Province	Albear and Iturralde-Vinent, 1985; Fonseca et al., 1989
HAV5	Boninites	Mafic rocks of the northern ophiolites	Southwest of the town of Campo Florido, outcrops along Central railroad near the small village of San Miguel, La Havana Province	Fonseca et al., 1989; Fonseca et al., 1990
MGT1	Basalts of the Margot Formation	Oceanic tholeiites of the northern ophiolites	Margot Mine inactive quarry, northeast end of the shaft of the mine, near the town of Corral Nuevo, Matanzas Province	Piotrowski and Myczyñski, 1986; Iturralde-Vinent 1996b
MGT2	Basalts of the Margot Formation	Oceanic tholeiites of the northern ophiolites	Margot Mine inactive quarry, northeast end of the shaft of the mine, near the town of Corral Nuevo, Matanzas Province	Piotrowski and Myczyñski, 1986; Iturralde-Vinent 1996b
SAG1	Basalts of the Sagua la Chica Formation	Oceanic tholeiites of the northern ophiolites	West bank of the Sagua la Chica River, below the bridge at the road from Santa Clara to Camajuaní, Villa Clara Province	Fonseca et al., 1990; Iturralde-Vinent, 1996b
SAG2	Dolerite block	Inclusions in the northern ophiolites	Small village named Crucero Carmita, East of Sagua la Chica River, on the road from Santa Clara to Camajuaní, Villa Clara Province	Iturralde-Vinent, 1996b
SAG3	Mafic block	Inclusions on the northern ophiolites	Small village named Crucero Carmita, East of Sagua la Chica River, on the road from Santa Clara to Camajuaní, Villa Clara Province	Iturralde-Vinent, 1996b
MAT1	Andesite in the Mataguá Formation	Cretaceous volcanic arc rocks ophiolites	Outcrop just north of the village Mataguá, on the road from Santa Clara to Manicaragua, Villa Clara Province	Villalvilla and Dilla, 1985; Pushcharovsky, 1988
MAT2 & 3	Igneous rocks in Mataguá Formation	Cretaceous volcanic arc rocks	1 km south of the village Mataguá, on the road to Manicaragua, Villa Clara Province	Villalvilla and Dilla, 1985;
MAT4	Basalt in the Mataguá Formation	Cretaceous volcanic arc rocks	Outcrop in Los Cocos, small village south of Mataguá, on the road from Santa Clara to Manicaragua, Villa Clara Province	Villalvilla and Dilla, 1985; Pushcharovsky, 1989
LPA1	Dacite of the Los Pasos Formation	Cretaceous volcanic arc rocks	Outcrop on the road from Santa Clara to Manicaragua, 3 km north of the town of Manicaragua, Villa Clara Province	Villalvilla and Dilla, 1985; Pushcharovsky, 1989
MAB1	Mabujina Amphibolites	High-T layered amphibolites	Outcrop on the road to Hotel Hanabanilla, near Loma Madera, north of the Hotel, Villa Clara Province	Iturralde-Vinent, 1996d, Millán, 1996b
NMA1	Basalt of Nueva María Formation	Continental margin rift tholeiites of the Bahamian borderland	Inactive quarry in Nueva María area, within the hills of Sierra de Camaján, Camagüey Province	Iturralde-Vinent and Marí, 1988, Iturralde-Vinent, 1996c
MUL1	Columnar basalts of La Mulata Formation	Cretaceous volcanic arc rocks	Large quarry named Turcios Lima, just north of the road from Minas to Nuevitas, 11 km southwest of the city of Nuevitas, Camagüey Province	Iturralde-Vinent, 1996d, 1996e
CAJ1	Andesite block in Camujiro Formation agglomerates	Cretaceous volcanic arc rocks	Small hill located just south of the village of Jimaguayú, south of Vidot, Camagüey Province	Iturralde-Vinent, 1996d, 1996e
COL1 & 2	Colombia basalts	Cretaceous volcanic arc rocks	Low limestone promontory located south and parallel to a dirt road heading northwest of Central (sugar mill) Colombia, on the way to the villages of Canario and Cuatro Caminos, Las Tunas Province	Rojas et al., 1995; Iturralde-Vinent, 1996d, 1996e
HOL2	Dolerite dike in layered gabbros	Dike complex in the northern ophiolites	Small outcrop at the intersection between the circunvalación and the road heading to Tacajó from the city of Holguín, Holguín Province	Andó et al., 1996
QUI1	Basalts of the Quiviján Formation	Oceanic tholeiites of the northern ophiolites	Large outcrops halfway on the road from Baracoa to Moa, west of Baracoa city, Guantánamo Province	Iturralde-Vinent, 1996b
QUI2	Basalts of the Quiviján Formation	Oceanic tholeiites of the northern ophiolites	Large outcrops halfway on the road from Baracoa to Moa, west of Baracoa city, Guantánamo Province	Iturralde-Vinent, 1996b

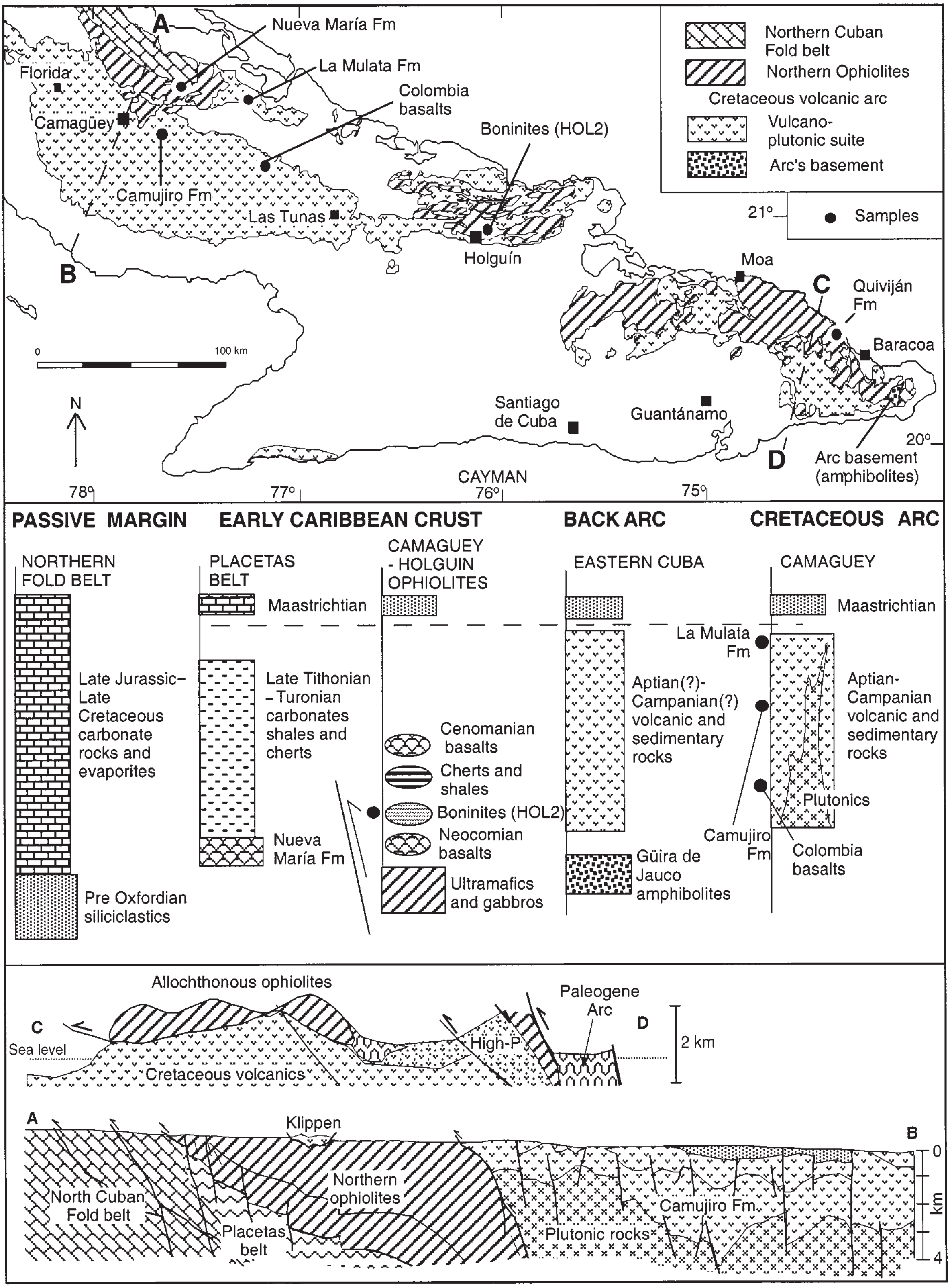

Figure 4. Sample map for eastern Cuba, showing geology, cross sections, and generalized stratigraphic sections.

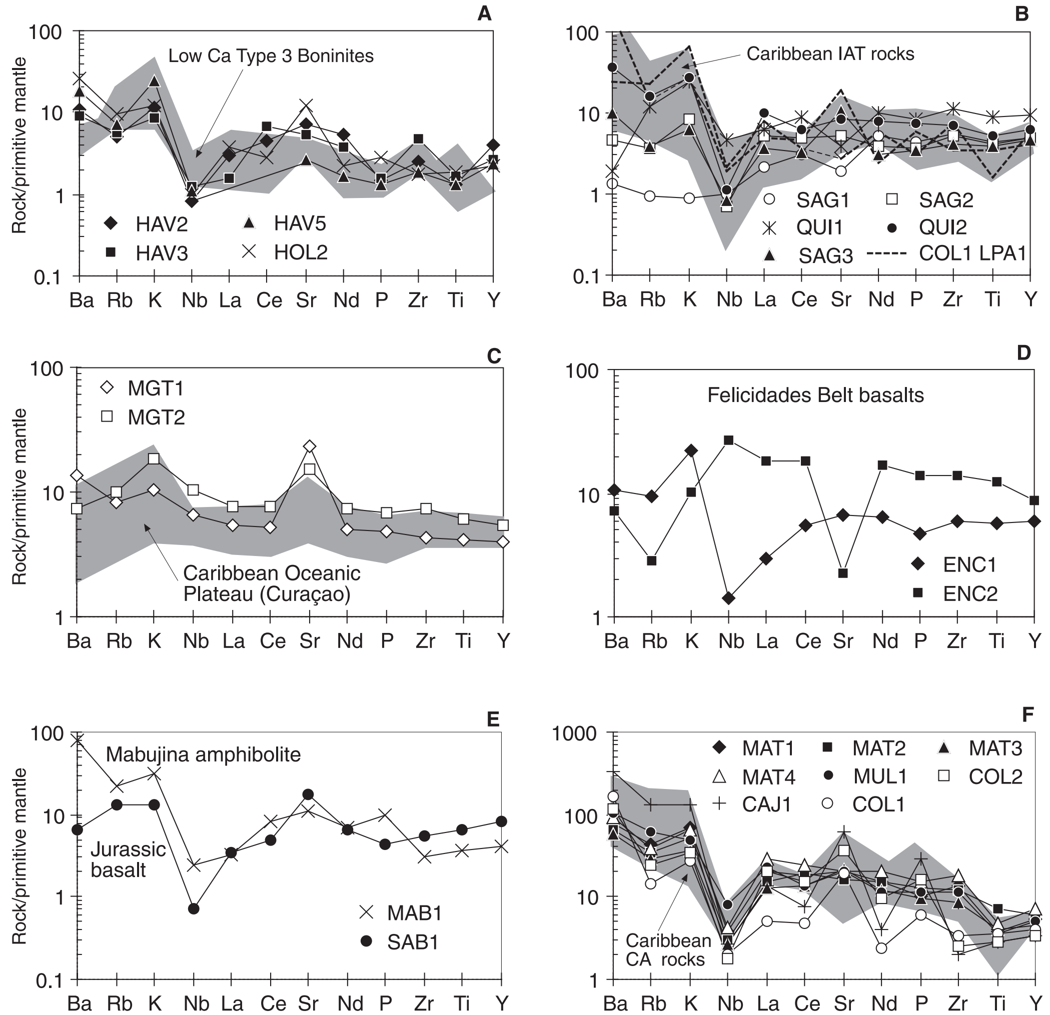

Figure 5. Primitive mantle-normalized multielement plots showing the different groups of Mesozoic igneous rocks found in Cuba. The gray shaded fields represent the composition of similar Cretaceous rocks from elsewhere in the Caribbean (and in the case of the boninites, the western Pacific). IAT—Island arc tholeiite. Data sources: Low-Ca type 3 boninites—Cameron et al. (1983); Hickey and Frey (1982); IAT (island arc tholeiites)—Donnelly and Rogers (1980); Beets et al. (1984); Donnelly et al. ( ); Lebrón and Perfit (1994); CA (calc-alkaline)—Donnelly et al. (1990); Donnelly and Rogers (1980); Lebrón and Perfit (1994); Caribbean oceanic plateau—Kerr et al. (1996b).

subduction-derived metamorphic rocks (eclogites and blue schists) have been found within the ophiolite melange. The rocks have been interpreted as Early Cretaceous age or older (Iturralde-Vinent et al., 1996; Millán, 1996a). This melange bears many lithological and tectonic similarities to a typical subduction accretion assemblage (cf. Barr et al., 1999)

Samples were collected from both the mafic dikes and the volcanic-sedimentary rocks all along the trend of the northern ophiolite melange (Fig. 1; Table 1). In the Havana area, samples HAV1–HAV5 represent boulders of dolerites and basalts embedded in deformed serpentinites and gabbros. From this locality, near San Miguel, Fonseca et al. (1989) described boninites of unknown age. In the region of Matanzas, samples (MGT1 and MGT2) were collected in Mina Margot from a large body (>1 km in diameter) of paleontologically dated volcanic-sedimentary rocks (Margot Formation) tectonically embedded in deformed serpentinites (Fig. 4; Table 1). This volcanic-sedimentary section comprises a 30- m-thick succession of Aptian-Albian pillow basalts interbedded with sediments, overlain by a 30-m-thick sequence of Cenomanian, tuffs, cherts, and shales with interbedded porphyritic basalts. On the basis of lithology and geochemistry, these rocks have been correlated with the Encrucijada and Quiñones Formations (Iturralde-Vinent, 1996b).

In central Cuba, a basalt sample (SAG1) was collected from the Tithonian Sagua la Chica Formation, which is composed of basalts intercalated with sediments and tuffaceous rocks (Llanes et al., 1998). Samples were also collected from blocks of dolerites (SAG2 and SAG3) found within deformed serpentinites (Fig. 4; Table 1). Near the city of Holguin, samples were collected from a dolerite boulder (e.g., HOL2) within deformed layered gabbros. The dolerites from Holguin yield inconclusive K-Ar whole-rock ages of 126.3 ± 8.3, 102 ± 20, 98.2 ± 5, and 57.8 ± 5.4 Ma (Iturralde-Vinent et al., 1996). In the east of Cuba, near the city of Baracoa, several large bodies of pillow basalts, 1–2 km wide, are found tectonically emplaced within serpentinites. These pillow basalts are intercalated with ribbon cherts, hyaloclastites, tuffaceous rocks, and some andesites, and the entire sequence is more than 500 m thick (Quiviján Formation: QUI1 and QUI2, Table 1).

The volcanic-sedimentary sections of oceanic tholeiites (represented by samples ENC1–2, MGT1–2, SAG1–3, QUI1–2) have been paleontologically dated as Tithonian-Campanian age (Figs. 2–4; Iturralde-Vinent, 1996b). However, these dates come from isolated fossiliferous samples recovered from pebbles and/or boulders or from thick stratigraphic units; thus they do not represent the complete age span of the sections. One possible interpretation is that these singular occurrences represent the original sedimentary deposits of the Caribbean crust, which have been deformed and dismembered in the melange. These rocks all have similar geochemical compositions (Fonseca et al., 1990; Iturralde-Vinent, 1996b; Fig. 5, B, C, and D).

Although the K-Ar whole-rock dates for the small boninite bodies found near Holguin should be treated with caution, the ages suggest that these rocks are 120–130 Ma or older (Andó et al., 1996). In spite of the fact that boninites have never been reported elsewhere in the Cuban volcanic-sedimentary ophiolite, or within the volcanic arc sections of the Greater Antilles, primitive island arc tholeiite rocks in Cuba and other Greater Antilles locations (Donnelly et al., 1990) are usually pre-Albian age. We suggest that the boninites associated with the northern ophiolite melange in Cuba are pre-Albian age.

Cretaceous Volcanic Arc and Its Basement

Rocks of island arc affinities have been widely recognized throughout Cuba (Fig. 1) (Iturralde-Vinent, 1996d, 1996e, 1996f). The Cretaceous arc rocks are in tectonic contact with the northern ophiolites, as well as with the Guaniguanico, Pinos, and Escambray terranes (Figs. 2–4).

It has been proposed that high-temperature amphibolites, metamorphosed volcanic-sedimentary sections, and plutonic rocks represent the basement of the Cretaceous arc (Iturralde-Vinent, 1994, 1996d, 1996e). This metamorphic basement can be found in eastern Cuba (Fig. 3) and in south-central Cuba, where they are known as the Mabujina amphibolites. These amphibolities, from which one sample has been collected (MAB1, Table 1; Fig. 2) underlie the less metamorphosed Cretaceous volcanic arc section (Somin and Millán, 1981; Millán, 1996b). In central Cuba the volcanic-sedimentary rocks of the arc have been subdivided into three sections on the basis of lithology and geochemistry (Iturralde-Vinent, 1994, 1996a, 1996d). The pre-Albian section is represented by the basalts and rhyolites of the Los Pasos Formation in south-central Cuba (Villalvilla et al., 1998). A large body of dacites north of Manicaragua (LPA1, Figs. 1 and 2; Table 1) was sampled during this study. Basalts and rhyolites of calc-alkaline composition overlie the Los Pasos Formation and are intercalated with sedimentary rocks of Albian to Coniacian age. Samples of basalts and andesites from these units were collected south of Santa Clara from the Albian-Cenomanian Mataguá Formation (MAT1-4, Figs. 1 and 2; Table 1), and near Camagüey from the mid-late Albian Colombia basalts (COL1-2) and from the Cenomanian-Turonian andesite-basalt agglomerates of the Camujiro Formation (CAJ1, Figs. 1 and 4; Table 1). The younger volcanic arc section, of Santonian-Campanian age, is represented by high alkaline-calc alkaline volcanic rocks. One sample from this section was collected northeast of the city of Camagüey, from the La Mulata Formation (MUL1, Figs. 1 and 4; Table 1), represented by columnar basalts of Campanian age (Iturralde-Vinent, 1996d). Plutonic rocks of arc affinities intrude both the amphibolites and the Cretaceous volcanic-sedimentary sections (Fig. 2).

Another Early Cretaceous volcanic arc may originally have existed, but it appears to have been aborted and mostly eroded away. The sparse evidence for this arc occurs in the form of plutonic, volcanic, and metamorphic rocks of arc affinities, found as pebbles in mid-late Albian conglomerates in several localities of western and central Cuba (Iturralde-Vinent, 1996f). Because these arc-derived conglomerates overlie the Lower Cretaceous rocks of the island arc tholeiite series within the Cretaceous arc, it is tentatively suggested that the source of these conglomerates was located elsewhere, possibly within the oceanic basin now represented by the ophiolite melange. The small plutonic bodies of arc affinities found within the ophiolite melange possibly represent the eroded roots of this remnant arc (Iturralde-Vinent, 1996f, 1997; Fig. 2).

Paleogene Arc

Paleocene to early Eocene island arc rocks are found predominantly in eastern Cuba (Iturralde-Vinent, 1994, 1996g). The southern axial part of the arc consists of calc-alkaline extrusive and pyroclastic rocks, intruded by granodiorite and granite plutons, whereas the northern (backarc) portion of the arc consists of pyroclastic and sedimentary rocks. Thin tuff layers representing this Paleogene volcanism are found within sedimentary successions throughout the rest of Cuba. These rocks were not sampled during this study.

SAMPLING STRATEGY AND ANALYTICAL METHODS

There are several major problems in sampling the Cuban igneous rocks. First, exposure is poor due to deep tropical weathering, and much of Cuba is covered by wild grass and farmland. Second, although an extensive series of boreholes have been drilled in a search for oil and minerals, most of the core recovered was not available for study. Third, the few exposures that exist are not only small in size, but the rocks are quite often very deeply weathered and altered. In several localities no samples were collected because of the extreme alteration of the rocks.

Samples were taken of volcanic rocks, including all major lithological units within Cuba (see also Fig. 1; Table 1). Locations of these samples are shown in Figure 1 and petrographic observations with more detailed field locations are summarized in Tables 1 and 2. Some of these samples (e.g., NMA1) proved to be too altered for geochemical analysis.

Analytical Methods

After powdering, major and trace elements were analyzed by X-ray fluorescence (XRF) at Leicester University using conventional techniques (see Kerr et al., 1996b, for further details). The rare earth elements Th, Co, Sc, Ta, and Hf were analyzed by Instrumental Neutron Activation Analysis (INAA) at the University of Leicester (see Fitton et al., 1998, for analytical details) (see Tables 3 and 4).

Alteration

Many of the Cuban rocks are badly altered and metamorphosed through the action of both high- and low-temperature fluids; as a result we concentrated our work on the least altered samples. With the exception of the Mabujina amphibolites (e.g., MAB1), greenschist facies is the highest metamorphic grade observed in the studied samples. More common alteration products are chlorite and serpentine (after olivine and occasional clinopyroxene) and sericitic alteration of plagioclase. The effects of this alteration can be observed in primitive mantle-normalized multielement plots that sometimes display a greater scatter for the most mobile elements such as K_2O, Na_2O, Ba, Rb, and Sr (Fig. 5). In contrast, the high field strength and the rare earth elements are generally more coherent, reflecting their relative immobility in these Cuban volcanic rocks. Samples belonging to the same type typically display little variation in elemental abundances or ratios between the most and least petrographically altered samples (Fig. 5). Thus we conclude that, although alteration has resulted in some minor redistribution of the more mobile elements, the concentrations and ratios of these elements can still be used with confidence to assess the petrogenetic history and original tectonic setting of the rocks. As a precaution, most of the following petrogenetic interpretations focus on the relatively more immobile elements.

CLASSIFICATION AND CHEMISTRY

Three main igneous suites have been identified within the circum-Caribbean Jurassic and Cretaceous sequences; the island arc tholeiite (IAT) series (primitive island arc; Donnelly and Rogers, 1980; Donnelly et al., 1990), the calc-alkaline series (Donnelly et al, 1990; Lebrón and Perfit, 1993), and the oceanic plateau series (Donnelly et al., 1990; Kerr et al., 1996c, 1997a, 1997b). Localized occurrences of Jurassic–Early Cretaceous mid-ocean ridge-like basalts have been inter-

TABLE 2 SUMMARY OF AGES, GEOCHEMICAL INTERPRETATION, AND PETROGRAPHY OF CUBAN VOLCANIC ROCKS

Geological setting	Sample	Formation	Age	Geochemical interpretation	Petrography
Rosario South belt	SAB1	El Sábalo	Oxfordian–early Kimmeridian	Rift basalt	Aphyric, fine to medium grained with altered plagioclase laths, interstitial clinopyroxene and anhedral oxides
Felicidades belt	ENC1	Encrucijada	Apt-Alb	Rift basalt	Fine to medium grained with altered plagioclase and olivine ENC1 has 2–3-mm-diameter altered plagioclase and twinned clinopyroxene phenocrysts
	ENC2	Encrucijada	Apt-Alb	Ocean island basalt	
Northern ophiolite mélange	HAV2	Mafic boulder	No data	Boninite	HAV2, medium grained, resorbed and regrown plagioclase, green clinopyroxene with kinked twinning. HAV3, Aphyric, Fine to medium grained with chloritized plagioclase and anhedral clinopyroxene few oxides HAV5, fine grained with chlorite pseudomorphed olivine micro phenocrysts. Altered groundmass composed of plagioclase needles clinopyroxene and oxides.
	HAV3	Mafic boulder	No data	Boninite	
	HAV5	Mafic boulder	No data	Boninite	
	MGT1	Margot	Aptian-Cenomanian	Oceanic plateau	MGT1, 2, Fine to medium grained with altered plagioclase, granular clinopyroxene and anhedral oxides contains a few carbonate veins.
	MGT2	Margot		Oceanic plateau	
	SAG1	Sagua La Chica	Tithonian	Island arc tholeiite	SAG1, Medium grained with altered plagioclase, subhedral clinopyroxene and anhedral oxides SAG2, medium grained, altered plagioclase anhedral oxide and clinopyroxene. SAG3 fine to medium grained clinopyroxene with plagioclase laths in a finer-grained groundmass.
	SAG2	Mafic boulder	No data	Island arc tholeiite	
	SAG3	Mafic boulder	No data	Island arc tholeiite	
	HOL2	Mafic boulder	L Cretaceous?	Boninite	HOL2, Aphyric fine to medium-grained, clinopyroxene replaced by amphibole with opaques and sericitized plagioclase
	QUI1	Quivijan	No data	Island arc tholeiite	QU1, fine-grained with reasonably fresh plagioclase and clinopyroxene. QUI2, altered plagioclase phenocrysts, plagioclase-rich altered groundmass.
	QUI2	Quivijan	No data	Island arc tholeiite	
Cretaceous volcanic arc	MAB1	Mabujina	Jurassic/L. Cretaceous	Island arc tholeiite	MAB1 Felted fine to medium grained mass of green amphibole, localized more felsic patches containing amphibole needles.
	LPA1	Los Pasos	Aptian/ Neocomian	Island arc tholeiite	LPA1, Fine grained, flow banded with aligned plagioclase laths, granular clinopyroxene and opaques. carbonate alteration patches and veins
	MAT1	Mataguá	Alb-Cenoman	Calc-alkaline arc	MAT1, Zoned plagioclase phenocrysts with marginal regrowth (3–4 mm) in a groundmass of MAT2, medium grained with altered plagioclase, clinopyroxene and anhedral oxides. MAT3, fine grained with altered plagioclase laths and clinopyroxene granules. MAT4, fine to medium-grained groundmass of plagioclase, clinopyroxene and opaques. Altered plagioclase and clinopyroxene phenocrysts (2–3 mm);
	MAT2	Mataguá	Alb-Cenoman	Calc-alkaline arc	
	MAT3	Mataguá	Alb-Cenoman	Calc-alkaline arc	
	MAT4	Mataguá	Alb-Cenoman	Calc-alkaline arc	
	CAJ1	Camujiro	Cenoman-Turonian	Calc-alkaline arc	CAJ1, Cpx phyric (2–3 mm). The medium-grained groundmass consists of altered plagioclase needles, granular clinopyroxene, oxide rhombs and possibly small olivine relics
	MUL1	La Mulata	Campanian Turonian	Calc-alkaline arc	MUL1, Fine-grained groundmass containing plagioclase laths, clinopyroxene and oxide granules. Abundant plagioclase (with inclusions) and sparse clinopyroxene phenocrysts (2–3 mm);
	COL1	Colombia basalts	Albian	Island arc tholeiite-Calc-alkaline arc	COL1, Glomerophyric clots of plagioclase and clinopyroxene in a fine grained groundmass of plagioclase laths and clinopyroxene granules. COL2, clinopyroxene and plagioclase phyric, groundmass similar to COL1
	COL 2	Columbia basalts	Albian		

TABLE 3. MAJOR AND TRACE ELEMENT X-RAY FLORESCENCE ANALYSES OF CRETACEOUS CUBAN VOLCANIC ROCKS

SiO_2	TiO_2	Al_2O_3	Fe_2O_3†	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total§	LOI#		V	Cr	Ba	Nb	Zr	Y	Sr	Rb	Ga	Ni	Th	Pb	La	Ce	Nd
Boninites																											
HAV2	59.18	0.29	15.51	7.12	0.12	5.58	8.85	2.48	0.339	0.032	99.50	0.63	194	128	75	0.6	28	18.6	152	3.2	15.9	69	1.3	1.9	2.1	7.9	7.1
HAV3	56.37	0.35	15.93	7.74	0.13	6.65	9.79	2.37	0.258	0.034	99.62	0.80	245	139	63	0.9	53	12.3	115	3.6	15.2	49	-	-	1.1	12.1	5.1
HAV5	55.13	0.29	13.60	8.45	0.18	11.71	8.27	1.74	0.754	0.028	100.15	2.91	203	494	130	0.8	21	10.8	55	4.6	11.9	197	-	2.9	1.3	2.5	1.4
HOL2	53.03	0.41	14.24	8.83	0.17	10.03	10.49	2.49	0.371	0.060	100.12	1.31	247	498	178	0.7	20	10.1	262	6.1	14.3	64	0.6	2.6	2.6	5.1	2.9
Island arc tholeiite series																											
SAG1	50.96	0.94	16.87	8.95	0.15	7.49	10.00	4.11	0.027	0.097	99.60	3.09	209	157	9	0.7	61	21.9	41	0.6	16.1	59	0.5	1.8	2.3	6.8	6.2
SAG2	51.79	0.92	16.22	9.03	0.16	7.44	9.07	4.22	0.258	0.081	99.19	2.53	212	174	32	0.5	57	22.9	112	2.3	15.6	68	0.7	1.0	3.6	9.0	5.3
SAG3	51.34	0.82	16.19	9.18	0.16	6.71	10.41	3.48	0.189	0.076	98.55	1.95	260	100	69	0.6	46	21.2	223	2.5	17	51	0.3	1.4	2.5	5.7	4.2
QUI1	49.13	1.90	14.14	11.44	0.22	7.61	10.41	3.07	0.720	0.186	98.83	2.61	372	175	14	3.4	125	43.2	83	7.5	20.3	59	1.1	2.0	3.9	12.6	11.6
QUI2	56.30	1.10	15.99	10.93	0.18	3.08	4.23	6.20	0.845	0.159	99.02	2.14	269	4	262	0.8	80	28.3	173	10.0	21.3	7	0.9	2.6	6.8	10.9	10.7
LPA1	73.44	0.35	12.67	2.41	0.07	0.72	2.46	5.26	1.949	0.068	99.40	2.44	12	12	167	1.5	82	26.7	58	14.2	13.3	4	-	0.3	3.6	9.0	8.5
COL1	49.31	0.77	19.50	11.04	0.21	4.90	10.02	3.03	0.831	0.128	99.73	1.27	319	19	1158	1.4	39	18.4	399	9.3	18.7	16	0.5	3.5	3.2	7.7	5.1
Oceanic intraplate lavas																											
MGT1	48.46	0.91	20.46	6.67	0.11	5.99	12.65	3.78	0.317	0.105	99.45	5.98	192	274	94	4.6	49	18.4	490	5.2	15.8	92	-	1.3	3.7	9.2	6.7
MGT2	50.80	1.31	17.84	6.15	0.12	7.09	12.15	4.04	0.550	0.148	100.20	5.61	221	418	52	7.3	83	24.9	324	6.3	14.3	141	0.5	1.5	5.3	13.5	10.0
ENC1	53.79	1.23	15.67	10.74	0.18	5.66	7.12	5.45	0.663	0.104	100.61	2.04	323	48	74	1.0	66	27	143	5.9	17.7	28	-	2.8	2.0	9.6	8.6
ENC2	40.96	2.68	14.38	15.42	0.35	9.62	14.49	0.85	0.311	0.307	99.36	2.83	421	272	50	18.8	153	39.8	47	1.8	20.5	110	1.7	2.4	12.3	32.2	22.6
Mabujina amphibolites																											
MAB1	48.18	0.81	13.70	11.76	0.20	9.06	12.95	1.31	0.947	0.210	99.13	0.72	330	287	551	1.7	34	18.8	233	14.3	16.4	61	0.5	4.6	2.2	14.4	9.3
Rift basalt																											
SAB1	50.26	1.42	13.75	13.35	0.25	7.29	8.44	3.87	0.406	0.095	99.13	1.91	369	61	46	0.5	63	36.6	365	8.4	19.6	47	0.3	4.0	2.4	8.8	8.8
Calc-alkaline suite																											
MAT1	56.48	0.83	16.74	6.97	0.18	2.79	9.87	3.55	2.095	0.225	99.73	3.04	231	31	534	2.7	155	24.8	427	27.0	19.3	13	1.8	5.1	14.4	31.6	20.5
MAT2	52.51	1.60	13.77	13.85	0.21	5.32	7.50	3.54	1.573	0.273	100.15	1.18	543	0	461	2.2	134	27.8	346	22.5	24.2	16	2.0	5.4	13.8	31.6	22.3
MAT3	52.68	0.89	17.72	9.94	0.16	4.86	9.55	3.13	1.086	0.212	100.22	0.91	292	33	403	1.9	97	20.7	469	18.1	21	19	2.3	4.9	8.7	24.6	16.6
MAT4	56.57	1.07	16.28	9.80	0.16	3.68	6.69	3.58	1.958	0.327	100.11	1.54	246	19	661	3.0	199	32.7	437	24.5	21.4	16	2.9	5.0	19.7	43.6	28.3
MUL1	61.42	0.76	17.08	6.67	0.13	2.48	6.42	3.73	1.455	0.243	100.39	1.10	157	6	706	5.7	125	22.7	421	39.8	17.5	9	1.8	6.0	16.0	24.7	15.6
CAJ1	49.74	0.62	13.16	10.75	0.19	7.64	9.82	2.67	3.874	0.636	99.10	1.99	284	167	2254	1.9	23	15.5	1305	82.7	12.6	65	1.1	7.5	9.3	13.6	5.5
COL2	50.85	0.60	14.06	10.80	0.17	7.46	11.33	2.90	1.055	0.362	99.59	1.64	308	159	831	1.3	29	15.6	784	15.3	14.9	39	3.4	6.6	13.9	27.2	13.3

†All Iron reported as Fe_2O_3.
§Major element totals reported on a volatile free basis.
#LOI—loss on ignition.

TABLE 4. REPRESENTATIVE INAA* ANALYSES OF CRETACEOUS CUBAN VOLCANIC ROCKS

	MGT1	MGT2	HOL2	HAV5	MAT2	LPA1	COL1	SAG1	QUI1	ENC2	JB-1a Measured	JB-1a Recommended
La	3.7	5.3	2.6	1.3	13.8	3.6	3.2	2.3	3.9	12.3	37.5	38
Ce	9.2	13.5	5.1	2.5	31.6	9.0	7.7	6.8	12.6	32.2	65.9	67
Nd	6.7	10.0	2.9	1.4	22.3	8.5	5.1	6.2	11.6	22.6	26.8	27
Sm	2.01	3.03	1.11	0.59	5.43	2.66	1.91	2.12	4.02	5.81	5.19	5
Eu	0.87	1.23	0.35	0.23	1.60	0.81	0.79	0.93	1.54	2.12	1.58	1.52
Tb	0.51	0.77	N.D.	N.D.	0.89	0.47	N.D.	N.D.	1.07	1.27	0.65	0.7
Yb	1.77	2.37	1.11	1.11	2.46	2.60	1.88	2.00	4.15	3.78	2.15	2.1
Lu	0.26	0.35	0.17	0.17	0.36	0.42	0.27	0.28	0.61	0.58	0.24	0.31
Ta	0.30	0.44	0.02	0.04	0.14	0.06	0.08	0.07	0.23	1.17	1.65	2
Th	0.41	0.60	0.55	0.29	1.89	0.59	0.55	0.17	0.26	0.56	9.81	8.8
Hf	1.54	2.28	0.72	0.65	3.96	2.59	1.40	1.59	3.28	4.37	3.71	3.4
Sc	28.5	41.6	48.9	37.9	46.9	14.5	36.6	34.0	45.2	45.9	29.0	29
Co	37.1	74.6	38.0	42.3	35.2	N.D.	32.4	36.9	42.6	54.7	39.5	N.D.

Note: N.D.—no data.
*INAA—instrumental neutron activation analysis.

preted as proto-Caribbean oceanic crust remnants (Donnelly et al., 1990; Kerr et al., 1997b) and continental rift basalts (Iturralde-Vinent, 1988, 1996c). The Cretaceous IAT series is generally older than the calc-alkaline series (Donnelly and Rogers, 1980), but in Puerto Rico and Cuba (Iturralde-Vinent, 1996a, 1996d; Schellekens, 1998), the two types are also partially isochronous.

The Cuban igneous rocks considered here can be divided into several types on the basis of geochemistry and tectonic setting. Petrographic observations and geochemical interpretations are listed in Table 2.

Rift Basalts

Jurassic basalts, which have been interpreted as having been formed in a rift-related continental margin on the basis of their stratigraphic position (Iturralde-Vinent, 1988, 1996d), are represented by one sample from El Sábalo Formation (SAB1, Table 2; Fig. 4). They are believed to have formed during the Oxfordian rifting event between the Yucatan (Maya block) and South America. SAB1 has a negative Nb anomaly, light rare earth element (REE) depletion, and a slight enrichment in the large ion lithophile elements (LILE) (Fig. 5E).

The two basalt samples (ENC1–2, Table 2) that belong to the Aptian-Albian Encrucijada Formation (Felicidades belt) differ markedly in their chemistry, ENC2 being much more enriched in incompatible trace elements than

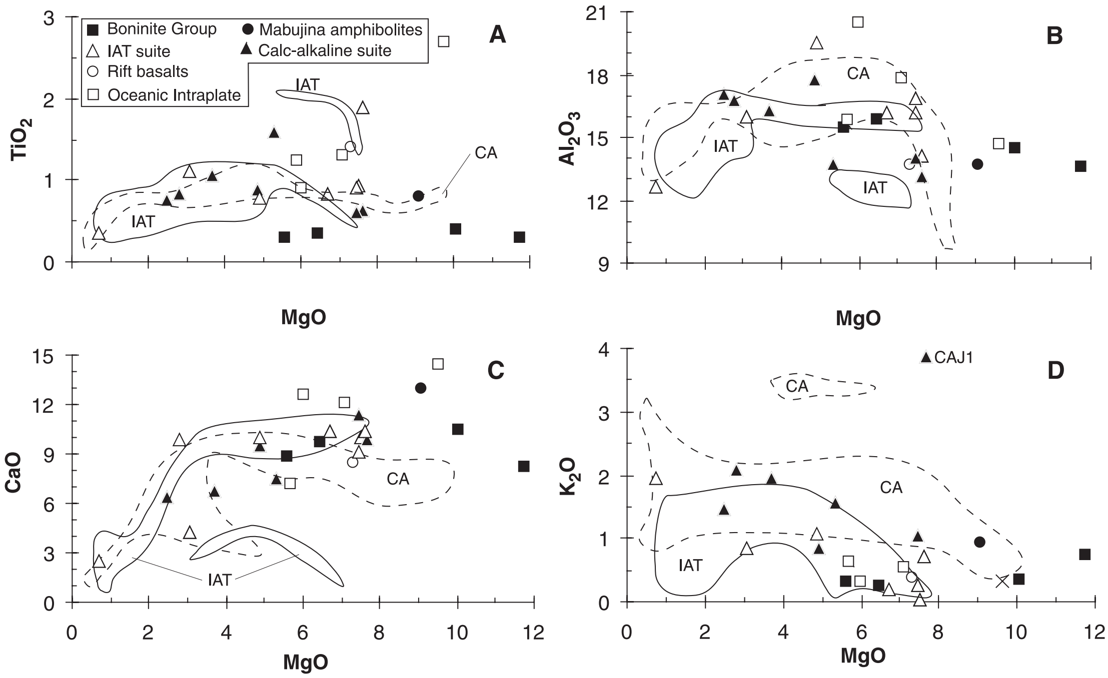

Figure 6. Plots of selected major elements against MgO for the Cuban Mesozoic igneous rocks with compositional fields for other Mesozoic Caribbean island arc tholeiites (IAT) and calc- alkaline (CA) rocks. Data sources as in Figure 5.

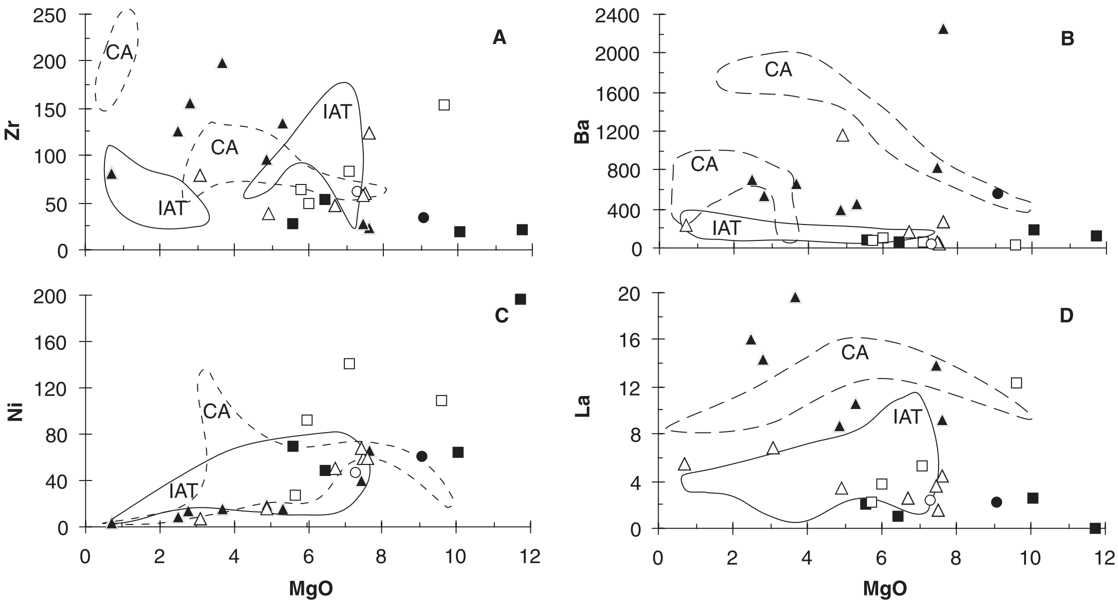

Figure 7. Plots of selected trace elements against MgO for the Cuban Mesozoic igneous rocks, with compositional fields for other Mesozoic Caribbean island arc tholeiites (IAT) and calc- alkaline (CA) rocks. Symbols as in Figure 6, data sources as Figure 5.

ENC1, and this despite being much more primitive (9.6 wt% MgO and 41 wt% SiO_2) than ENC1 (5.7 wt% MgO and 54 wt% SiO_2) (Fig. 6). Thus, these lavas were not derived from the same parental magma. Further differences also highlight this point: first, ENC2 has a light REE enriched normalized pattern (Fig. 8), whereas ENC1 has a depleted light REE pattern (Fig. 5D), similar to mid-ocean ridge basalt (MORB). Second, ENC1 has a marked negative Nb anomaly (Fig. 5), whereas ENC2 has a slight positive Nb anomaly. Sample ENC2 has a steep REE pattern (Fig. 8), and most closely resembles modern-day ocean island basalts. Samples ENC1 and SAB1, despite being of different ages and tectonostratigraphic positions, appear to have been derived from a similar source region and were possibly contaminated by the same crustal material.

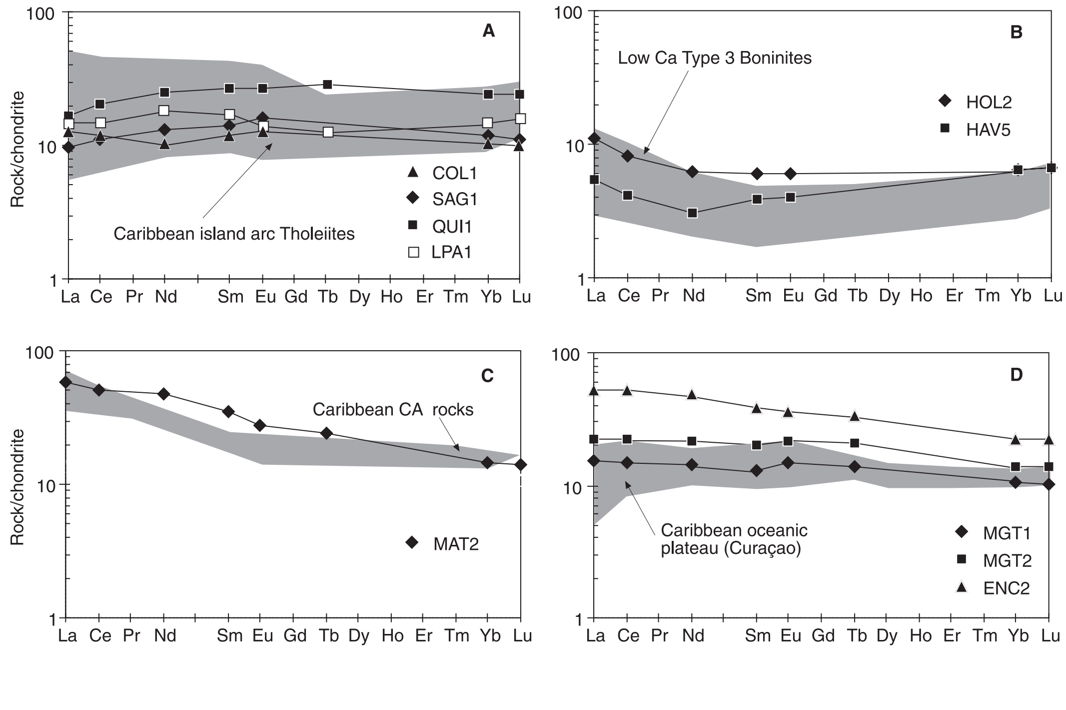

Figure 8. Rare earth element chondrite-normalized plots showing a representative set of Cuban Mesozoic igneous rocks. Also shown for comparison are shaded fields representing the range of composition of similar Caribbean (and Pacific) rocks and low-Ca type 3 boninites from the Bonin Islands and Cape Vogel. Data sources are as in Figure 5.

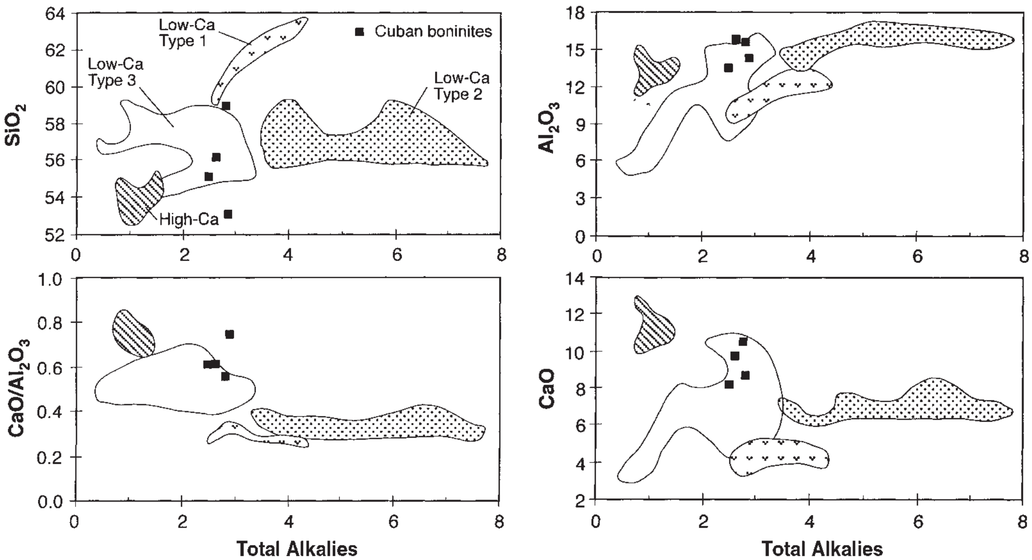

Figure 9. Plots of major elements and ratios against total alkalies ($K_2O + Na_2O$) showing the Cuban boninites. Also shown are compositional fields for the various types of boninites defined by Crawford et al. (1989). It can be seen that the Cuban boninites broadly fall within the field of low-Ca type 3 (from the Bonin Islands and Cape Vogel).

Taken together, these geochemical characteristics suggest an asthenospheric source region for these basalts, possibly a mantle plume.

Oceanic Intraplate Lavas

Two basalt samples from the Aptian-Albian volcanic-sedimentary Margot Formation that occur within the northern ophiolite melange (MGT1 and MGT2, Table 2) are moderately enriched in the light REEs ($[(La/Y]_n$ ~1.5; Figs. 5C and 8D) and thus they cannot be classed as depleted normal MORB. In addition to this, these basalts do not possess significant negative Nb anomalies and are not significantly enriched in the LILEs (Fig. 5C), and so it would seem unlikely that they were generated in a subduction-related setting, i.e., they cannot be classed as belonging to the IAT or calc-alkaline series. The relatively flat primitive mantle normalized multielement patterns displayed by these lavas bear close similarities to Late Cretaceous basalts found in western Colombia (South America) and the southern Caribbean (Figs. 5C and 8D), which have been shown to be a part of a mantle plume-derived oceanic plateau (Kerr et al., 1997a, 1997b, 1996b). We therefore suggest that the basalts of the Margot Formation be classed as oceanic intraplate lavas and could either have formed a part of the 90 Ma Caribbean oceanic plateau (Kerr et al., 1997b) or could represent part of the proto-Caribbean oceanic crust.

Boninites

These lavas are represented by samples HOL1, HAV2, HAV3, and HAV5, and were collected from the northern ophiolite melange (Table 2; Figs. 3 and 4). Only two of the samples (HAV5 and HOL1) fulfil the exact criteria for classification as a boninite (>53 wt% SiO_2 and > 0.6 Mg#; Crawford et al., 1989). The trends for these lavas in Figures 5, 6, and 7 strongly suggest that HAV2 and HAV3 have been derived by fractional crystallization from a high-MgO boninite, similar in composition to HAV5.

HAV5 possesses 11.7 wt% MgO and can be classed as a high-MgO basaltic andesite (Fig. 5); the most evolved flow of the group is an andesite containing 59 wt% SiO_2 and 5.6 wt% MgO. Figure 5A shows that HAV5 has negative anomalies at Rb and Nb, with small negative anomalies at P and Ti which get progressively deeper as the rocks of the suite become more evolved. Although HOL1 has a lower (53 wt%) SiO_2 content, than the other boninites, it has similar trace element patterns (Fig. 8B and 5A) to the HAV samples, and has a relatively high MgO content (10.0 wt%).

Boninites have been divided into two main types; high (>10 wt%) and low CaO boninites (Crawford et al., 1989). Low-CaO boninites have been subdivided into types 1, 2, and 3 (see Fig. 9). The Cuban boninite suite belongs to the type 3 low-CaO boninite group, the characteristics of which are low total alkali content (<3 wt%) and high FeO(T) (>8 wt%) and CaO/Al_2O_3 (0.5–0.8) (Fig. 9).

The Cuban boninites are similar in composition to other low Ca type 3 boninites (Fig. 9) and also have distinctive U-shaped chondrite-normalized REE patterns (Fig. 8B), which are nearly identical to some of the other type 3 boninites.

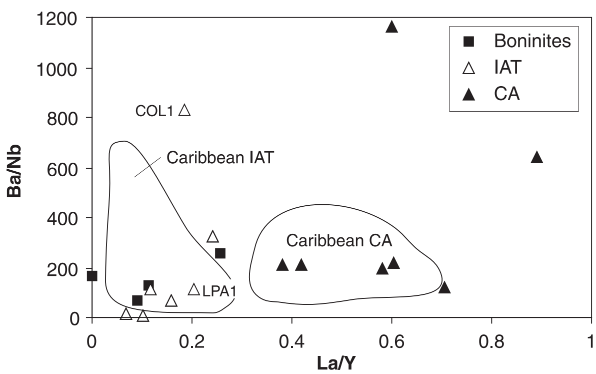

Figure 10. Plot of Ba/Nb against La/Y showing the arc-related Mesozoic Cuban igneous rocks along with fields for other Mesozoic Caribbean rocks of the island arc tholeiites (IAT) and calc-alkaline (CA) series. Data sources as in Figure 5.

These U-shaped patterned, type 3 low-CaO boninites may result from mixing a light REE-depleted magma with a light REE-enriched subduction-related fluid (Cameron et al., 1983).

Boninites have not been reported elsewhere from the Caribbean region, either among the Cretaceous arc rocks or the more recent subduction-related rocks, and the significance of this discovery is discussed in the following.

Island Arc Tholeiite (IAT) Series

In the northern ophiolite melange these lavas are represented by small blocks and complete sections of basalts (e.g., SAG1–3, QUI1) with occasional andesites (e.g., QUI2) (Fig. 6). They have lower MgO and higher abundances of incompatible trace elements at a given SiO_2 content than the boninites (Figs. 6 and 7).

In contrast to the boninites, these lavas have relatively flat patterns amongst the more compatible elements (Nd to Y; Fig. 5B), a feature that is also borne out by the relatively flat REE patterns (Fig. 8A). With one exception (SAG1), the lavas are moderately enriched in the LILEs, resulting in negative Nb anomalies. SAG1 is not enriched in the LILEs, has no negative Nb anomaly, and has a similar composition to normal MORB (Fig. 5B). As discussed here, this sample may well have formed in a backarc basin. These basaltic lavas have close chemical similarities (relatively low levels of K_2O, Ba, and Rb) to other Cretaceous arc basalts around the margins of the Caribbean (Figs. 5 and 7). The backarc affinity is supported by the MORB-like chondrite-normalized REE patterns of the basaltic samples within the Cuban IAT series (SAG1–3, QUI1–2; Fig. 8A), and by the backarc chemistry of other Cretaceous basalts described from Cuban ophiolites (Fonseca et al., 1990; Iturralde-Vinent, 1996b).

Another example of a possible IAT series rock is sample MAB1 (collected from the Mabujina amphibolites, Fig. 2; Table 1), which is most similar in terms of its trace element composition to the more depleted members of the calc-alkaline series (especially COL1; Fig. 5). However, MAB1 has some similarities to the IAT series (Figs. 6 and 7). Somin and Millán (1981), Millán (1996b), and Iturralde-Vinent (1989, 1994, 1996a) considered these amphibolites to represent the pre-Aptian oceanic basement of the arc.

Two samples, LPA1 and COL1, belonging to the Cretaceous island arc have lower levels of incompatible trace elements than the rest of the Cretaceous island arc samples that belong to the calc-alkaline suite (Figs. 5F and 7). As Figures 5B and 8C show, in many respects they are similar in composition to the IAT series. Note that these two samples have Th and Pb contents that are significantly lower than in the calc-alkaline sample (Table 4).

IAT series rocks have been reported elsewhere in the Caribbean region, and have been dated Aptian-Albian or older (Donnelly et al., 1990; Lebrón and Perfit, 1994; Schellekens, 1998). Figures 5B and 6–8 reveal that the IAT samples from Cuba largely are within the same compositional range as the IAT rocks from the rest of the Caribbean province (Figs. 5–8 and 10). Figure 5B shows that both the Cuban samples and those from the rest of the Caribbean possess similar trace element patterns. The moderate enrichment in the LILEs (Fig. 5B) is also reflected in the low La/Y ratios (<0.3) of the IAT series (relative to the calc-alkaline series; Fig. 10).

Calc-Alkaline Series

This suite of rocks was collected within the late Albian through Campanian volcanic arc section in central Cuba (Figs. 2 and 3; Table 2) and are generally more evolved than the IAT series. They range in composition from low MgO basalts (e.g., CAJ1) through andesites (Fig. 6) to (Iturralde-Vinent, 1996a, 1996d). As well as being slightly more evolved, the calc-alkaline rocks are more enriched in Ba, K, Rb, Sr, Th, Pb, and the light REEs than the IAT series (Figs. 5F, 8C, and 10). CAJ1 is the most magnesian calc-alkaline series lava and is more enriched in LILEs (Sr, Pb, Th, and P) than the rest of the calc-alkaline lavas (Figs. 5F, 6, and 7). It bears some similarities to high-potassium lavas found within the Cretaceous calc-alkaline series in the rest of the Caribbean, particularly those in Hispanola (Lebrón and Perfit, 1994) and Puerto Rico (Jolly, 1971; Donnelly and Rogers, 1980; Schellekens, 1998).

Calc-alkaline magmas have been erupted in the Caribbean region since Cretaceous time until the present day and, although the calc-alkaline series is generally younger than the IAT series, they overlap in age (Donnelly et al., 1990; Iturralde-Vinent, 1996d; Schellekens, 1998). The Cretaceous calc-alkaline series (preserved as both plutons and volcanic rocks) are found throughout Central America, the Greater Antilles, and northern South America (Donnelly et al., 1990; Schellekens, 1998). In several Caribbean localities, as in the Camagüey province of Cuba, these calc-alkaline rocks are highly potassic (shoshonitic) (Jolly, 1971; Donnelly et al., 1971, 1990; Lebrón and Perfit, 1994; Iturralde-Vinent, 1996d; Schellekens, 1998). Some of these calc-alkaline rocks from the circum-Caribbean region are plotted in Figures 5–8 and most of the Cuban calc-alkaline series are within the compositional range of the other Caribbean calc-alkaline rocks (Figs. 5F, 6–8, and 10). All of the calc-alkaline Caribbean rocks have a greater negative Ti anomaly than the IAT series (Fig. 5F), and are all more enriched in the LILEs and light REEs than the IAT series (Figs. 5–8 and 10).

DISCUSSION

In this section we discuss the implications of our Cuban study for plate tectonic models of the Caribbean region. Three main topics are considered: the early opening of the Caribbean; the early volcanic arc systems, and later volcanic arc systems and the evolution of the Caribbean plate.

Early Opening of the Caribbean

The El Sábalo Formation basalts (SAB1) differ from the other Cuban basalts in terms of both their thickness (~400 m) and their age (Oxfordian–early Kimmeridgian). The geochemical characteristics of El Sábalo basalts are consistent with formation at a continental rift margin, and may analogous to the ca. 60 Ma volcanism associated with the break up of the North Atlantic (cf. Fitton et al., 1998). Most plate tectonic reconstructions suggest that these continental rift margins were formed during the separation of the Yucatan (Maya block) from northern South America in Jurassic time (Fig. 11) (e.g., Duncan and Hargraves, 1984; Burke, 1988; Ross and Scotese, 1988).

The Albian-Aptian (97–125 Ma) oceanic intraplate lavas (MGT1–2) and the Encrucijada basalts (ENC1–2) also appear to be essentially unrelated to subduction, and they could have formed in two possible locations: either in the Pacific (on the Farallon or Phoenix plate) or the proto-Caribbean plate. The Encrucijada Formation basalts may represent fragments of the proto-Caribbean oceanic basin (Iturralde-Vinent, 1994, 1996b, 1997). The chemistry of the lavas (ENC1–2) supports this model, in that ENC2 has a distinctly ocean island basalt–like chemistry, and may have been formed in an intraplate setting. Although ENC1 has a MORB-like chondrite normalized REE pattern and a negative Nb anomaly, it is possible that it is also a plume-related magma that was erupted through, and contaminated by, continental crust on the Yucatan–South America continental margin (cf. the ca. 60 Ma plume-related volcanism associated with the opening of the North Atlantic; Saunders et al., 1997; Fitton et al., 1998).

More outcrops of Mesozoic oceanic basalts have been reported from the Dominican Republic (195–165 Ma Early Jurassic Duarte complex), from Puerto Rico (Pliensbachian-Aptian Bermeja Complex), La Desirade (Late Jurassic), and northern Venezuela (Middle Jurassic Bathonian-Bajocian Siquisique basalts (Bartok et al., 1993; Montgomery et al., 1994; Schellekens, 1998). The occurrence of Early Jurassic–Early Cretaceous

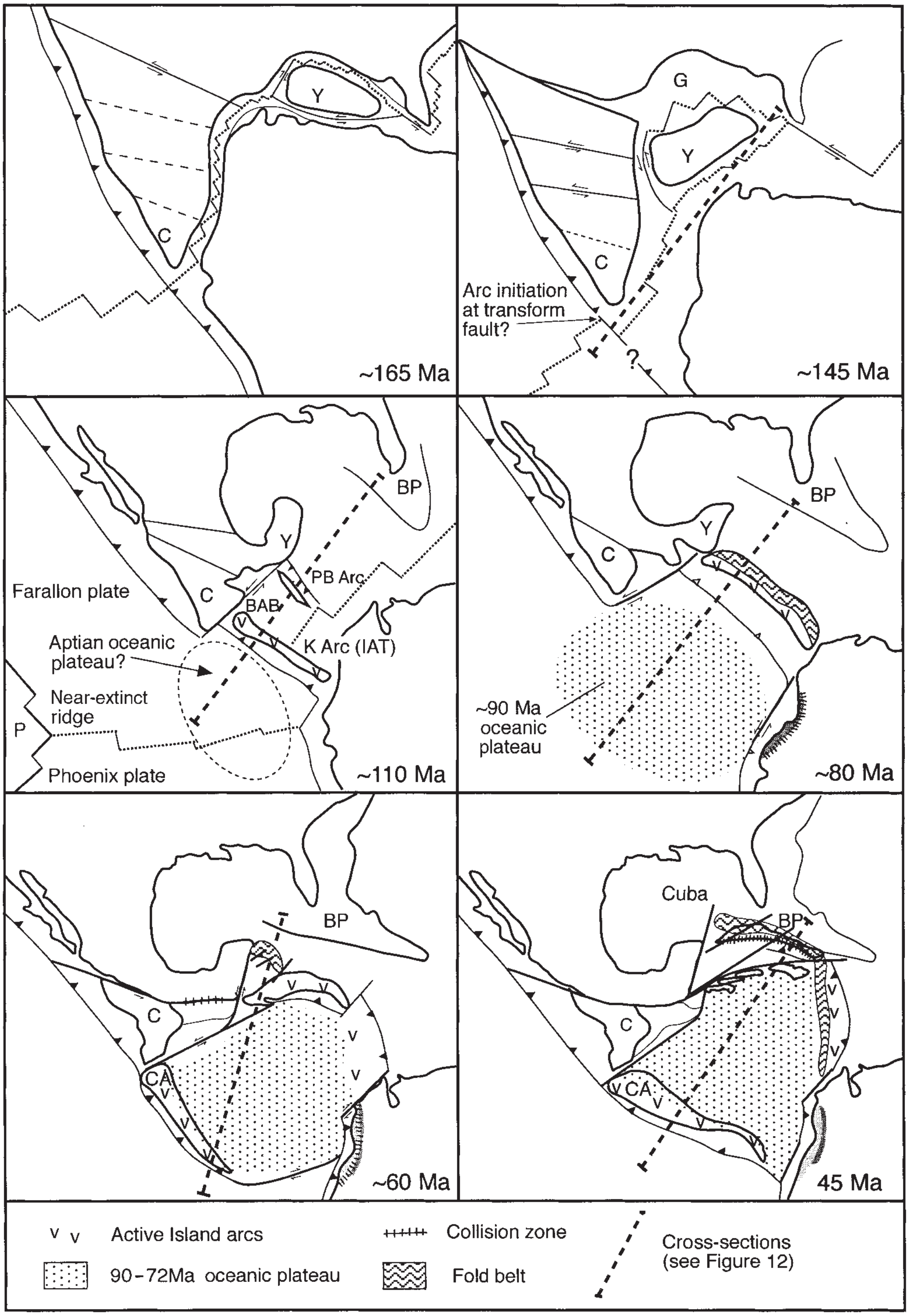

Figure 11. Plate reconstruction models for the Caribbean region from Late Jurassic to Early Cretaceous time, based on Pindell and Dewey (1982), Duncan and Hargraves (1984), Burke (1988), and Ross and Scotese (1988). Abbreviations: Y—Yucatan block (peninsula); C—Chortis block; G—Gulf of Mexico; BP—Bahamas platform; BAB—backarc basin; PB Arc—primitive boninite arc; CA—Central America; K Arc—Cretaceous arc.

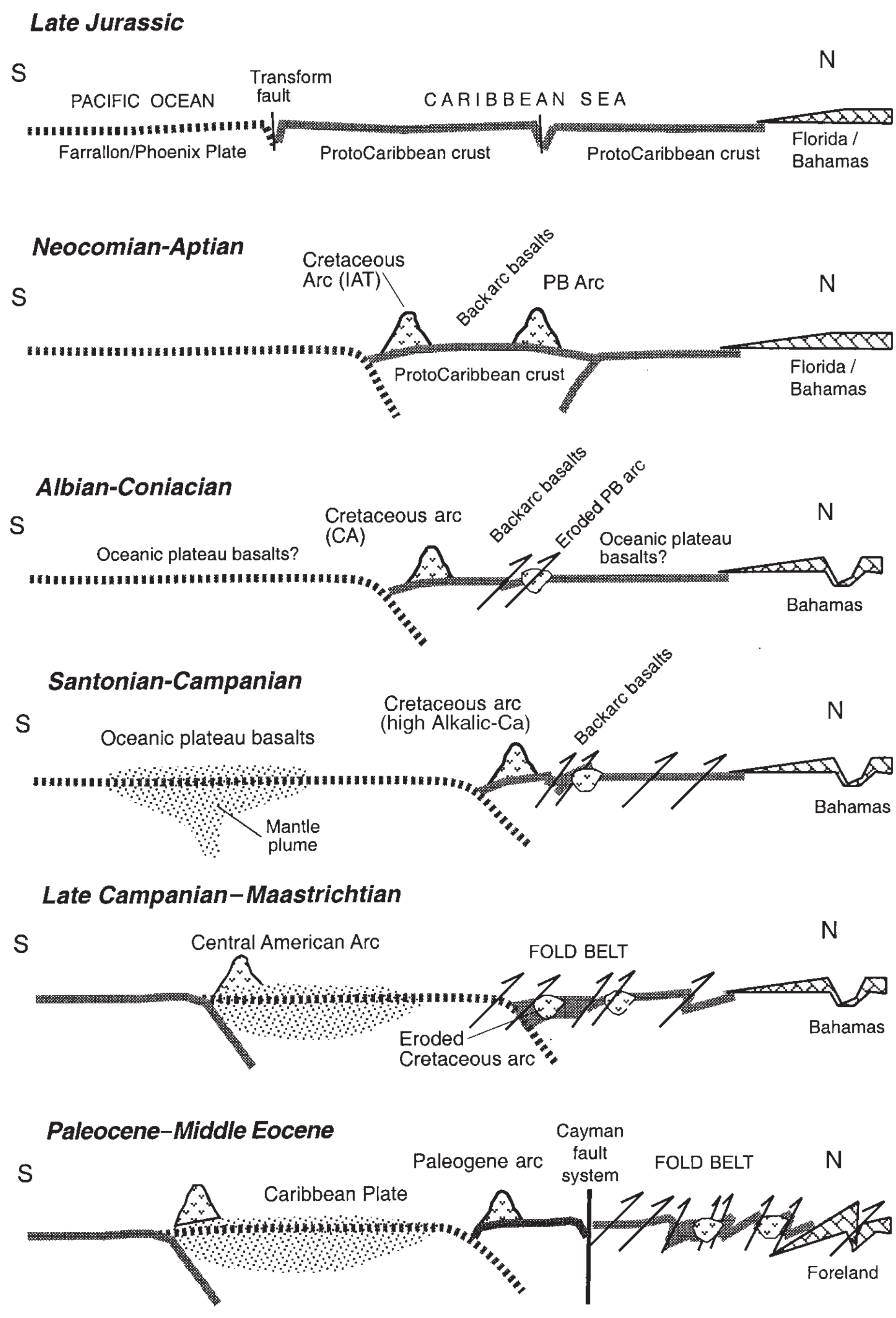

Figure 12. Latest Jurassic to middle Eocene plate tectonic evolutionary cross sections of the Caribbean area. Cross section locations are shown in Figure 11. PB Arc—primitive boninite arc; IAT—island arc tholeiite.

basic flows, sills, and dikes within the passive margin sections of the Guaniguanico, Pinos, and Escambray terranes (Iturralde-Vinent, 1988, 1996c) suggests that the Caribbean seaway began to open in Early Jurassic time.

We have suggested that the oceanic intraplate lavas (MGT1–2) may represent the remnants of an oceanic plateau. This suggestion is given further support by the fact that Albian-Aptian time was one of major plateau-forming events in the Pacific (Mahoney et al., 1993) and thus these Cuban lavas may represent a part of this event. Whether these lavas actually formed in the Pacific, or are also part of the proto-Caribbean ocean floor, is not clear. The absence of any sign of sialic crustal contamination (e.g., a negative Nb anomaly) tends to support a Pacific origin for these basalts (i.e., eruption away from a continental margin) (Figs. 11 and 12). However, the Margot Formation basalts are tectonically intermixed with island arc and backarc basalts of the northern ophiolites, and so the association of a Pacific-derived oceanic plateau with these other Caribbean-derived tectonic units argues against a Pacific origin in this case.

Even though the provenance of these Margot Formation basalts remains in doubt, it seems clear that they are similar in chemistry to, and may therefore be part of, an oceanic plateau, which probably formed an area of thicker and more buoyant crust. These basalts formed either on the Farallon-Phoenix or proto-Caribbean plate and were accreted against the Antillean arc system, possibly in Albian-Cenomanian time (112–91 Ma) (cf. Kerr et al., 1997a, 1997b; Lapierre et al., 1997).

Early Arc Systems

According to most interpretations of Caribbean tectonics, an arc system developed around the Jurassic-Cretaceous boundary, possibly along an older oceanic ridge located between the Pacific and proto-Caribbean plate (Burke, 1988; Pindell and Barrett, 1990). This arc gradually moved into the opening gap between North and South America. However, the problem is complicated by our geochemical results, which suggest the occurrence of two parallel isochronous arc systems in the mesoamerican region in the early stages of arc formation.

Primitive Boninite Arc. One volcanic arc edifice is probably represented by the latest Jurassic–Early Cretaceous boninites from the northern ophiolite melange of Cuba. According to Crawford et al. (1989), type 3 boninites are derived from somewhat less-refractory harzburgites than type 1 boninites, and melting probably occurred in the upper mantle at depths of less than 30 km and at temperatures greater than 1200 °C. The heat required for boninite genesis could be provided by subduction of an active spreading center subparallel to the trench, i.e., the subduction of young hot oceanic lithosphere (Crawford et al., 1989). Alternatively, the initiation of a new subduction zone at a transform fault, in the manner suggested by Stern and Bloomer (1992), may result in boninite genesis. Duncan and Hargraves (1984) and Burke (1988) suggested that the initiation of Antillean arc system in the western Pacific (before its eastward migration) occurred at a fracture zone (or transform fault) associated with

the Farallon-Phoenix spreading center. The absence of arc rocks younger than Albian within the northern ophiolites of Cuba, and the abundance of arc-derived clastic material in Albian conglomerates, suggest that this arc became extinct early in Cretaceous time (Fig. 12). High-pressure metamorphic inclusions in the northern ophiolite melange (Millán, 1996a) may represent the exhumed subduction zone of the primitive boninite arc. Because the remnants of the arc are now northeast of the Cretaceous arc (Fig. 2), one can suggest that both volcanic edifices originally lined up trending roughly north-south, parallel to the western edge of the American plates. We suggest that the subduction zone of the primitive boninite arc dipped southward because Tithonian through Campanian backarc volcanic-sedimentary sections occur in association with the northern ophiolites, and this backarc basin may be genetically related to the evolution of the Cretaceous arc located to the south (Figs. 11 and 12).

Cretaceous Arc (IAT Suite). The Cretaceous arc volcanic suite is represented by the pre-mid Albian IAT rock suite of Cuba (including the Mabujina MAB1, Los Pasos LPA1, and Colombia COL1 samples), the Devil's Racecourse Formation of Jamaica, the Los Ranchos Formation, Maimon schists and the Guamira basalts of the Dominican Republic, the Pre-Robles volcanics of Puerto Rico, and the Water Island Formation of the Virgin Islands.

The IAT suite of the Cretaceous arc began to form around the time of the Jurassic-Cretaceous boundary and was active until Albian time. After this activity, two more suites evolved, the calc-alkaline and high alkaline–calc-alkaline. These later suites lasted until Albian-Coniacian time (calc-alkaline suite) and Santonian-Campanian time (high alkaline–calc-alkaline suite). Magmatic rocks of calc-alkaline and high alkaline arc affinities have been described in Cuba, and from other places in the Caribbean area (see Donnelly et al., 1990, for a review).

Recent models for the location and polarity of the subduction zone of the Cretaceous arc (IAT, calc-alkaline, and high alkaline–calc-alkaline suites) suggest that it was located south of the Cretaceous arc and that the slab dipped northward (e.g., Iturralde-Vinent, 1994, 1997b; Rosencrantz, 1996; Schellekens, 1998). This view is corroborated by the location of the backarc basin north of the Cretaceous arc (Figs. 11 and 12).

Evolution of the Caribbean Plate and Later Arc Systems

Throughout Cretaceous time the Antillean arc system gradually moved into the widening ocean basin between North and South America (Fig. 11; Burke, 1988; Ross and Scotese, 1988; Iturralde-Vinent, 1998). Eastward movement was probably due to subduction polarity reversal from east to westward dipping (Ross and Scotese, 1988; Pindell, 1994). Lebrón and Perfit (1993, 1994) proposed that this subduction flip was pre-Aptian age and led to a change in the geochemical signature of the arc from IAT to calc-alkaline.

Lebrón and Perfit (1993, 1994) speculated that this subduction flip was caused by the arrival and attempted subduction of the pre-Albian Caribbean plateau. However, recent high-precision $^{40}Ar/^{39}Ar$ dating has shown that the vast bulk of the oceanic plateau crust in and around the Caribbean is 91–88 Ma (Kerr et al., 1996a, 1997a; Sinton et al., 1998), and is not pre-Aptian in age. Thus, the model of Lebrón and Perfit (1993, 1994) would seem to be untenable because, although subduction flip appears to have been hastened by attempted subduction of the thicker and more buoyant Caribbean oceanic plateau, this actually commenced in Late Cretaceous time (Figs. 11 and 12; Burke, 1988; Kerr et al., 1997b; White et al., 1999).

There is also significant evidence from Cuba and elsewhere to suggest that the change from IAT to calc-alkaline–type volcanism was not abrupt (sensu Lebrón and Perfit, 1994). On the basis of exposures in the Dominican Republic and Puerto Rico, Donnelly et al. (1971, 1990) proposed that the change was more gradual. In addition, several lavas (COL1 and LPA1) within the later Cuban Cretaceous arc belong to the IAT series. This evidence is at variance with the model of Lebrón and Perfit (1994) and implies that the source region of the IAT magmas was still available during the later episode of arc volcanism.

The change in source required by the Pb isotope systematics of the IAT series compared to the more LILE-enriched calc-alkaline series, strongly suggests that the calc-alkaline series (which is clearly transitional to the IAT series) possesses more of an input from radiogenic continental-derived sediments (Donnelly et al., 1971; Lebrón and Perfit, 1994). The inference is that as the arc moved into the proto-Caribbean realm from the Pacific, the closer proximity to both North and South America resulted in the subduction of a greater proportion of continental-derived sediments (with more radiogenic Pb isotopes). It is likely that this contributed to the formation of the generally younger (Aptian-Campanian, 124–74 Ma) calc-alkaline series in the Caribbean region. We propose that the formation of IAT series magmas (along with calc-alkaline magmas) be interpreted as representing periods when less terrestrial sediment was subducted, either because it was not present on the subducting slab, or because it was scraped off during subduction. This eastward movement of the Antillean arc appears to have been hastened by the geometry of the gap between the North and South American plates; thus in Late Cretaceous time a new arc (the Central American arc) formed by the subduction of the Farallon plate below the thicker and more buoyant Caribbean oceanic plateau (Fig. 11).

A basic difference between our plate tectonic model and other models (e.g., Burke et al., 1984; Ross and Scotese, 1988; Pindell, 1994) concerns the position and polarity of the subduction zone, which in our model is located south of the Cretaceous arc and dips northward (Iturralde-Vinent, 1994, 1996a, 1997b). This subduction zone has been traced in southern Cuba (Iturralde-Vinent, 1994, 1996a; Rosencrantz, 1996) and crops out as the Bermeja complex in southwest Puerto Rico (Schellekens, 1998). Early Jurassic to Aptian radiolarian cherts found in association with normal MORB basalts, amphibolites, and ultramafic rocks in the Bermeja complex (Schellekens, 1998) are correlatable with Cretaceous arc evolution. This subduction zone was only active until Campanian-Maastrichtian time, when volcanism ended in the Cretaceous arc along the Greater Antilles and the Cordillera del Caribe of Venezuela (Iturralde-Vinent, 1996a, 1997a, 1997b).

The insertion of the Caribbean plate in the gap between North and South American plates was due to the differential rate of plate movements and associated shortening (superposition, deformation, and amalgamation) within the in situ Caribbean crust (Figs. 11 and 12). Most of this shortening took place during Cenozoic time (Bralower and Iturralde-Vinent, 1997), probably as a reaction to the cessation of subduction activity in the Cretaceous arc, and the formation of the Central American arc in Campanian time, thus creating a new Pacific-Caribbean plate boundary. In this context, the Caribbean oceanic plateau basalt province was isolated from the Pacific by the Central American arc, and was emplaced into its present position during Cenozoic time.

CONCLUSIONS

1. We suggest that some of the basalts found among the accreted Cuban terranes were formed during the rifting between North and South America and as such represent part of the proto-Caribbean oceanic crust. The oceanic tholeiites are similar in composition to Cretaceous plume-derived oceanic plateau basalts from the Pacific. These Cuban basalts may also mantle plume derived, and originated either in the Pacific or possibly in the proto-Caribbean.

2. New evidence for the occurrence of Cretaceous backarc rocks within the northern ophiolite melange of Cuba is in agreement with a northward-dipping subduction zone for the Early Cretaceous Antillian arc.

3. The discovery of type 3 boninites within deformed ophiolites in northern Cuba support

the coexistence of two Early Cretaceous (pre-Albian arcs) in the Caribbean realm. The primitive boninite arc was aborted and largely eroded away during early Albian time, but the other arc (the Cretaceous arc) continued activity until Campanian time.

4. The Cretaceous arc comprises three different geochemical suites; the island arc tholeiite suite, the calc-alkaline suite, and the high-alkaline–calc-alkaline suite. The early period of the arc is dominated by island arc tholeiites, but as the input of continental-derived sediments into the subduction zone increases, the calc-alkaline suite gradually becomes more important.

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REFERENCES CITED

Albear, J., and Iturralde-Vinent, M., 1985, Estratigrafía de las provincias de La Habana, *in* Iturralde-Vinent, M. A., ed., Contribucion a la geologia de las provincias de La Habana y Ciudad de La Habana: La Habana, Editorial Cientìfico-Tècnica, p. 12–54.

Andó, J., Harangi, S., Szkmány, B., and Dosztály, L., 1996, Petrología de la Asociación Ofiolítica de Holguín, *in* Iturralde-Vinent, M. A., ed., Cuban ophiolites and volcanic arcs: Miami, Florida, International Geological Correlation Programme 364, p. 154–178.

Barr, S. R., Temperley, S., and Tarney, J., 1999, Lateral growth of the continental crust through deep level subduction-accretion: A re-evaluation of Central Greek Rhodope: Lithos, v. 46, p. 69–94.

Bartok, P. E., 1993, Prebreakup geology of the Gulf of Mexico–Caribbean: Its relations to Triassic and Jurassic rift systems of the region: Tectonics, v. 12, p. 441–459.

Beets, D. J., Maresch, W. V., Klaver, G. T., Mottana, A., Bocchio, R., Beunk, F. F., and Monen, H. P., 1984, Magmatic rock series and high-pressure metamorphism as constraints on the tectonic history of the southern Caribbean, *in* Bonini, W. E., Hargraves, R. B., and Shagam, R., eds., The Caribbean–South America plate boundary and regional tectonics: Geological Society of America Memoir 162, p. 95–130.

Bralower, T., and Iturralde-Vinent, M., 1997, Micropaleontological dating of the collision between the North American plate and the Greater Antilles Arc in western Cuba: Palaios, v. 12, p.133–150.

Burke, K., 1988, Tectonic evolution of the Caribbean: Annual Reviews of Earth and Planetary Science, v. 16, p. 201–230.

Burke, K., Fox, P. J., and)Şengör, M. C., 1978, Buoyant ocean floor and the origin of the Caribbean: Journal of Geophysical Research, v. 83, p. 3949–3954.

Burke, K., Cooper, C., Dewey, J. F., Mann, P., and Pindell, J. L., 1984, Caribbean tectonics and relative plate motions, *in* Bonini, W. E., Hargraves, R. B., and Shagam, R., eds., The Caribbean–South America plate boundary and regional tectonics: Geological Society of America Memoir 162, p. 31–64.

Cameron, W. E., McCulloch, M. T., and Walker, D. A., 1983, Boninite petrogenesis: Chemical and Nd-Sr isotopic constraints: Earth and Planetary Science Letters, v. 65, p. 75–89.

Case, J. E., MacDonald, W. D., and Fox, P. J., 1990, Caribbean crustal provinces; seismic and gravity evidence, *in* Dengo, G., and Case, J. E., eds., The Caribbean region: Boulder, Colorado, Geological Society of America, Geology of North America, v. H, p. 15–36.

Crawford, A. J., Falloon, T. J., and Green, D. H., 1989, Classification petrogenesis and tectonic setting of boninites, *in* Crawford, A. J., ed., Boninites and related rocks: London, Unwin Hyman Ltd., p. 1–44.

Cruz, E. A., 1998, Sedimentos vinculados al complejo de basaltos en la región de Bahía Honda, Cuba, *in* Geología y Minería 98, Memórias, v. 2, p. 224–226.

Cruz, E. A., and Simón, A., 1992, Principales rasgos del complejo de basaltos de Bahía Honda, Pinar del Río: 13th Caribbean Geological Conference, Programs and Abstracts, p. 108.

Dengo, G., and Case, J. E., eds., 1990, The Caribbean region: Boulder, Colorado, Geological Society of America, Geology of North America, v. H,

Donnelly, T. W., 1973, Late Cretaceous basalts from the Caribbean, a possible flood basalt province of vast size: Eos (Transactions, American Geophysical Union), v. 54, p. 1004.

Donnelly, T. W., 1989, Geologic history of the Caribbean and Central America, *in* Bally, A. W., and Palmer, A. R., eds., An overview: Boulder, Colorado, Geological Society of America, Geology of North America, v. A, p. 299–321.

Donnelly, T. W., and Rogers, J. J. W., 1980, Igneous series in island arcs: The northeastern Caribbean compared with worldwide island arc assemblages: Bulletin of Volcanology, v. 43, p. 347–382.

Donnelly, T. W., Rogers, J. J. W., Pushkar, P., and Armstrong, R. L., 1971, Chemical evolution of the igneous rocks of the eastern West Indies: An investigation of thorium, uranium, and potassium distributions, and lead and strontium isotope ratios, *in* Donnelly, T. W., ed., Caribbean geophysical, tectonic, and petrologic studies: Geological Society of America Memoir 130, p. 181–224.

Donnelly, T. W., Beets, D., Carr, M. J., Jackson, T., Klaver, G., Lewis, J., Maury, R., Schellenkens, H., Smith, A. L., Wadge, G., and Westercamp, D., 1990, History and tectonic setting of Caribbean magmatism, *in* Dengo, G., and Case, J. E., eds., The Caribbean region: Boulder, Colorado, Geological Society of America, Geology of North America, v. H, p. 339–374.

Duncan, R. A., and Hargraves, R. B., 1984, Plate tectonic evolution of the Caribbean region in the mantle reference frame, *in* Bonini, W. E., Hargraves, R. B., and Shagam, R., eds., The Caribbean–South America plate boundary and regional tectonics: Geological Society of America Memoir 162, p. 81–93.

Edgar, N. T., Ewing, J. I., and Hennion, J., 1971, Seismic refraction and reflection in the Caribbean Sea: American Association of Petroleum Geologists Bulletin, v. 55, p. 833–870.

Fitton, J. G., Saunders, A. D., Larsen, H. C., Hardarson, B. S., and Norry, M. J., 1998, Volcanic rocks from the East Greenland margin at 63°N: Composition, petrogenesis and mantle sources, *in* Saunders, A. D., Larsen, H. C., and Wise, S., Proceedings of the Ocean Drilling Program, Scientific results, Volume 152: College Station, Texas, Ocean Drilling Program, p. 331–350.

Fonseca, E. R., González, R., and Savieleva, G., 1989, Presencia de efusivos ofiolíticos y de boninitas en las provincias de La Habana y Matanzas: Boletín Técnico, Geología, Ministerio de Industria Básica, v. 1, p. 1–9.

Fonseca, E., Castillo, F., Uhanov, A., Navarrete, M., and Correa, G., 1990, Geoquímica de la associación ofiolítica de Cuba: Transactions of the 12th Caribbean Geological Conference, St. Croix, U.S. Virgin Islands, p. 51–58.

Hickey, R. L., and Frey, F. A., 1982, Geochemical characteristics of boninite series volcanics: Implications for their source: Geochimica et Cosmochimica Acta, v. 46, p. 2099–2115.

Hutson, F., Mann, P., and Renne, P., 1998, $^{40}Ar/^{39}Ar$ dating of single muscovite grains in Jurassic siliciclastic rock (San Cayetano Formation): Constraints on the paleoposition of western Cuba: Geology, v. 26, p. 83–86.

Iturralde-Vinent, M. A., 1988, Consideraciones generales sobre et magmatismo de margen continental de Cuba: Revista Tecnológica, v. 18, p. 17–24.

Iturralde-Vinent, M. A., 1989, Role of ophiolites in the geological constitution of Cuba: Geotectonics, v. 4, p. 63–74.

Iturralde-Vinent, M. A., 1994, Cuban geology: A new plate tectonic synthesis: Journal of Petroleum Geology, v. 17, p. 39–70.

Iturralde-Vinent, M. A., 1996a, Introduction to Cuban geology and geophysics, *in* Iturralde-Vinent, M. A., ed., Cuban ophiolites and volcanic arcs: Miami, Florida, International Geological Correlation Programme 364, p. 3–35.

Iturralde-Vinent, M. A., 1996b, Geología de las ofiolitas de Cuba, *in* Iturralde-Vinent, M. A., ed., Cuban ophiolites and volcanic arcs: Miami, Florida, International Geological Correlation Programme 364, p. 83–120.

Iturralde-Vinent, M. A., 1996c, Magmatismo de margen continental de Cuba, *in* Iturralde-Vinent, M. A., ed., Cuban ophiolites and volcanic arcs: Miami, Florida, International Geological Correlation Programme 364, p. 121–130.

Iturralde-Vinent, M. A., 1996d, Cuba: El arco de islas volcanicas del Cretacico, *in* Iturralde-Vinent, M. A., ed., Cuban ophiolites and volcanic arcs: Miami, Florida, International Geological Correlation Programme 364, p. 179–189.

Iturralde-Vinent, M. A., 1996e, Estratigrafía del arco volcánico Cretácico de Cuba, *in* Iturralde-Vinent, M. A., ed., Cuban ophiolites and volcanic arcs: Miami, Florida, International Geological Correlation Programme 364, p. 190–226.

Iturralde-Vinent, M. A., 1996f, Evidencias de un arco Primitivo (Cretácico Inferior) en Cuba, *in* Iturralde-Vinent, M. A., ed., Cuban ophiolites and volcanic arcs: Miami, Florida, International Geological Correlation Programme 364, p. 227–230.

Iturralde-Vinent, M. A., 1996g, Cuba: El archipielago volcanico del Paleoceno-Eoceno medio, *in* Iturralde-Vinent, M. A., ed., Cuban ophiolites and volcanic arcs: Miami, Florida, International Geological Correlation Programme 364, p. 231–246.

Iturralde-Vinent, M. A., 1998, Introducción a la geología de Cuba, *in* Furrazola Bermúdez, G., and Núñez Cambra, K., eds., Estudios sobre Geologia de Cuba: La Habana, Centro Nacional de Informacion Geologica, p. 35–68.

Iturralde-Vinent, M. A., and Mari Morales, T., 1988, Toleitas del Tithoniano de la Sierra de Camajan, Camaguey: Posible datacion de la corteza oceanicia: Revista Tecnológica, v. 18, p. 25–32.

Iturralde-Vinent, M. A., Millan, G., Korpas, L., Nagy, E., and Pajon, J., 1996, Geological interpretation of the Cuban K-Ar data base, *in* Iturralde-Vinent, M. A., ed., Cuban ophiolites and volcanic arcs: Miami, Florida, International Geological Correlation Programme 364, p. 48–69.

Jolly, W. T., 1971, Potassium-rich igneous rocks from Puerto Rico: Geological Society of America Bulletin, v. 82, p. 399–408.

Kerr, A. C., Marriner, G. F., Arndt, N. T., Tarney, J., Nivia, A., Saunders, A. D., and Duncan, R. A., 1996a, The petrogenesis of komatiites, picrites and basalts from the Isle of Gorgona, Colombia; new field, petrographic and geochemical constraints: Lithos, v. 37, p. 245–260.

Kerr, A. C., Tarney, J., Marriner, G. F., Klaver, G. T., Saunders, A. D., and Thirlwall, M. F., 1996b, The geochemistry and petrogenesis of the late Cretaceous picrites and basalts of Curacao, Netherlands Antilles: A remnant of an oceanic plateau: Contributions to Mineralogy and Petrology, v. 124, p. 29–43.

Kerr, A. C., Tarney, J., Marriner, G. F., Nivia, A., Saunders, A. D., and Klaver, G. T., 1996c, The geochemistry and tectonic setting of Late Cretaceous Caribbean and Colombian volcanism: Journal of South American Earth Sciences, v. 9, p. 111–120.

Kerr, A. C., Marriner, G. F., Tarney, J., Nivia, A., Saunders, A. D., Thirlwall, M. F., and Sinton, C. W., 1997a, Cretaceous basaltic terranes in western Colombia: Elemental,

chronological and Sr-Nd constraints on petrogenesis: Journal of Petrology, v. 38, p. 677–702.
Kerr, A. C., Tarney, J., Marriner, G. F., Nivia, A., and Saunders, A. D., 1997b, The Caribbean-Colombian Cretaceous igneous province: The internal anatomy of an oceanic plateau, *in* Mahoney, J. J., and Coffin, M., eds., Large igneous provinces; continental, oceanic and planetary flood volcanism: American Geophysical Union Monograph 100, p. 123–144.
Khudoley, C., 1967, Principal features of Cuban geology: American Association of Petroleum Geologists Bulletin, v. 51, p. 668–677.
Lapierre, H., Dupuis, V., de Lepinay, B. M., Ruiz, J., Tardy, M., Maury, R. C., Hernandez, J., and Loubet, M., 1997, Is the lower Duarte igneous complex (Northern Hispanola) a remnant of the Caribbean plume-generated oceanic plateau?: Journal of Geology, v. 105, p. 111–120.
Lebrón, M. C., and Perfit, M. R., 1993, Stratigraphic and petrochemical support subduction polarity reversal of the Cretaceous Caribbean island arc: Journal of Geology, v. 101, p. 389–396.
Lebrón, M. C., and Perfit, M. R., 1994, Petrochemistry and tectonic significance of Cretaceous island arc rocks, Cordillera Central, Dominican Republic: Tectonophysics, v. 229, p. 69–100.
Llanes, A. L., García, D. E., and Meyerhoff, D. H., 1998, Hallazgo de fauna jurásica (Tithoniano) en ofiolitas de Cuba central, *in* Geología y Minería 98, Memórias, v. 2, p. 241–244.
Mahoney, J. J., Storey, M., Duncan, R. A., Spencer, K. J., and Pringle, M., 1993, Geochemistry and age of the Ontong Java Plateau, in Pringle, M. S., ed., The Mesozoic Pacific: Geology, tectonics and volcanism: American Geophysical Union Monograph 77, p. 233–261.
Meyerhoff, A. A., and Meyerhoff, H. A., 1972, Continental drift IV: The Caribbean plate: Journal of Geology, v. 80, p. 34–60.
Millán, G., 1996a, Metamorfitas de la asociación ofiolítica de Cuba, *in* Iturralde-Vinent, M. A., ed., Cuban ophiolites and volcanic arcs: Miami, Florida, International Geological Correlation Programme 364, p. 131–146
Millán, G., 1996b, Geología del complejo Mabujina, *in* Iturralde-Vinent, M. A., ed., Cuban ophiolites and volcanic arcs: Miami, Florida, International Geological Correlation Programme 364, p. 147–153.
Montgomery, H., Pessagno, E. A., and Pindell, J. L., 1994, A 195 Ma terrane in a 165 Ma Sea: Pacific origin of the Caribbean Plate: GSA Today, v. 4, p. 1–7.
Pardo, G., 1975, Geology of Cuba, in The ocean basins and margins: New York, Plenum Press, p. 553–613.
Pindell, J. L., 1985, Alleghenian reconstruction and subsequent evolution of the Gulf of Mexico, Bahamas and the Proto-Caribbean: Tectonics, v. 4, p. 1–39.
Pindell, J. L., 1990, Geological arguments suggesting a Pacific origin for the Caribbean plate, *in* Larue, D. K., and Draper, G., eds., Transactions of the 12th Caribbean Geological Conference, St. Croix, Virgin Islands: Miami, Florida, Miami Geological Society, p. 1–4.
Pindell, J. L., 1994, Evolution of the Gulf of Mexico and the Caribbean, *in* Donovan, S. K., and Jackson, T. A., eds., Caribbean geology, An introduction: Kingston, Jamaica, University of the West Indies Publishing Association, p. 13–40.
Pindell, J. L., and Barrett, S. F., 1990, Geologic evolution of the Caribbean region: A plate tectonic perspective, *in* Dengo, G., and Case, J. E., eds., The Caribbean region: Boulder, Colorado, Geological Society of America, Geology of North America, v. H, p. 405–432.
Pindell, J. L., and Dewey, J. F., 1982, Permo-Triassic reconstruction of western Pangea and the evolution of the Gulf of Mexico/Caribbean region: Tectonics, v. 1, p. 179–211.
Piotrowski, J., and Myczynski, R., 1986, Los depósitos vulcanógeno-sedimentarios de la zona Zaza de la provincia de Matanzas: Polish Academy of Earth Sciences Bulletin, v. 34, p. 49–66.
Pszczolkowski, A., 1978, Geosynclinal sequences of the Cordillera de Guaniguanico in western Cuba; their lithostratigraphy, facies development and paleogeography: Acta Geologica Polonica, v. 28, p. 1–96.
Pushcharovsky, Y., ed., 1988, Geological map of the Cuban Republic: Academy of Sciences of Cuba and USSR, 42 sheets, scale 1:250 000.
Rosencrantz, E., 1996, Basement structure and tectonics in the Yucatan basin, *in* Iturralde-Vinent, M. A., ed., Cuban ophiolites and volcanic arcs: Miami, Florida, International Geological Correlation Program Project 364, p. 36–47.
Ross, M. L., and Scotese, C. R., 1988, A hierarchical tectonic model of the Gulf of Mexico and Caribbean region: Tectonophysics, v. 155, p. 139–168.
Saunders, A. D., Fitton, J., Kerr, A. C., Norry, M. J., and Kent, R. W., 1997, The North Atlantic Igneous Province, *in* Mahoney, J. J., and Coffin, M., eds., Large igneous provinces; continental, oceanic and planetary flood volcanism: American Geophysical Union Monograph 100, p. 45–93.
Schellekens, J. H., 1998, Geochemical evolution and tectonic history of Puerto Rico, *in* Lidiak, E. G., and Larue, D. K., eds., Tectonic and geochemistry of the northern Caribbean: Geological Society of America Special Paper 322, p. 35–66.
Schubert, C., 1935, Historical geology of the Antillian-Caribbean region: New York, Hafner, 811 p.
Sinton, C. W., Duncan, R. A., Storey, M., Lewis, J., and Estrada, J. J., 1998, An oceanic flood basalt province within the Caribbean plate: Earth and Planetary Science Letters, v. 155, p. 221–235.
Somin, M., and Millán, G., 1981, Geology of the metamorphic complexes of Cuba: Moscow, Nauka, 218 p. (in Russian).
Stern, R. J., and Bloomer, S. H., 1992, Subduction-zone infancy: Examples from the Eocene Izu-Bonin-Mariana and Jurassic California arcs: Geological Society of America Bulletin, v. 104, p.1621–1636.
Uyeda, S., and Miyashiro, A., 1974, Plate tectonics and the Japanese Islands: A synthesis: Geological Society of America Bulletin, v. 85, p. 1159–1170.
Villalvilla, L., and Dilla, M., 1985, Proposición para una división de la llamada Formación Tobas (Provincias Cienfuegos, Villa Clara y Sancti Spiritus): Serie Geológica del CIG, v. 1, p. 133–149.
Villalvilla, L., Miliá, I., and Santa Cruz, M., 1998, Ambiente volcánico en el Cretácico Temprano de Cuba Central: su significación petrogénica y económica, *in* Geología y Minería 98, Memórias, v. 2, p. 327–230.
White, R. V., Tarney, J., Kerr, A. C., Saunders, A. D., Kempton, P. D., and Klaver, G. T., 1999, Modification of an oceanic plateau, Aruba, Dutch Caribbean: Implications for the generation of continental crust: Lithos, v. 46, p. 43–68.
Zelepuguin, V., Fonseca, E., and Díaz de Villalvilla, L., 1982, Asociaciones vulcanógenas de la provincia de Pinar del Río: Centro de Investigaciones Geológicas de Cuba, Serie Geológica, v. 6, p. 42–74.

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