IN-SITU U-PB SECONDARY ION MASS SPECTROMETRY (IN-SIMS)

GEOCHRONOLOGY FROM THE LEEWARD ANTILLES ISLANDS OF ARUBA,

CURAÇAO, BONAIRE, AND GRAN ROQUE: IMPLICATIONS FOR THE TEMPORAL

EVOLUTION OF THE CARIBBEAN LARGE IGNEOUS PROVINCE (CLIP) AND EARLY

ARC MAGMATISM

by

CHRISTOPHER G. HUMPHREY

(Under the Direction of James E. Wright)

ABSTRACT

In-situ U-Pb secondary ion mass spectrometry (IN-SIMS) was performed on both micro-baddeleyite and micro-zircon from mafic samples of the Leeward Antilles islands of Aruba, Curaçao, Bonaire, and Gran Roque in order to gain a better understanding of the temporal evolution of both the Caribbean large igneous province (CLIP) and early arc magmatism. IN-SIMS analysis of CLIP samples from Aruba, Curaçao, and Gran Roque indicate a ~30 m.y. span of CLIP magmatism from the Aptian to Coniacian (ca. 115-87 Ma). The extensive duration of CLIP magmatism argues against the formation of the CLIP within a few million years (e.g. Sinton et al., 1998; Kerr et al., 2003). IN-SIMS geochronological results from Bonaire in addition to U-Pb SHRIMP data from Wright and Wyld (2010) indicate that early arc activity occurred on Bonaire from the Albian to Cenomanian (ca. 112-95 Ma).

INDEX WORDS: Caribbean Large Igneous Province (CLIP), IN-SIMS geochronology, oceanic plateau, large igneous province (LIP), Leeward Antilles, Aruba, Curaçao, Bonaire, Gran Roque

IN-SITU U-PB SECONDARY ION MASS SPECTROMETRY (IN-SIMS)

GEOCHRONOLOGY FROM THE LEEWARD ANTILLES ISLANDS OF ARUBA,

CURAÇAO, BONAIRE, AND GRAN ROQUE: IMPLICATIONS FOR THE TEMPORAL

EVOLUTION OF THE CARIBBEAN LARGE IGNEOUS PROVINCE (CLIP) AND EARLY

ARC MAGMATISM

by

CHRISTOPHER G. HUMPHREY

B.S., The University of North Carolina at Chapel Hill, 2008

A Thesis Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment

of the Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2010

IN-SITU U-PB SECONDARY ION MASS SPECTROMETRY (IN-SIMS)

GEOCHRONOLOGY FROM THE LEEWARD ANTILLES ISLANDS OF ARUBA,

CURAÇAO, BONAIRE, AND GRAN ROQUE: IMPLICATIONS FOR THE TEMPORAL

EVOLUTION OF THE CARIBBEAN LARGE IGNEOUS PROVINCE (CLIP) AND EARLY

ARC MAGMATISM

by

CHRISTOPHER G. HUMPHREY

Major Professor:	James E. Wright
Committee:	Sandra Wyld
	Robert Hawman

Electronic Version Approved:

Maureen Grasso
Dean of the Graduate School
The University of Georgia
August 2010

ACKNOWLEDGEMENTS

I want to thank Dr. Jim Wright for all of his time and help throughout my thesis. I learned a lot from the entire thesis writing process and feel that I am a much better scientist after working with Dr. Wright. The opportunity to travel to Venezuela and the ability to truly see Venezuela for what it is was a once in a lifetime experience.

I would also like to thank my committee members Dr. Sandra Wyld and Dr. Robert Hawman for all of their helpful input. Their revisions were vital to making my thesis into a finished product.

I am very appreciative for the hospitality and time of Dr. Franco Urbani and Luis Melo. They did an incredible job showing us Venezuela and allowing us to have a safe and successful journey.

My work at UCLA was made possible by Dr. Kevin Chamberlain and Dr. Axel Schmitt. They dedicated a lot of time to this process and helped me so much during those long nights using the ion-probe.

Financial support was provided by the National Science Foundation and the Wheeler-Watts Fund.

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

CHAPTER 1

<u>INTRODUCTION</u>

Large igneous provinces (LIP) are enormous crustal emplacements of mafic extrusive and intrusive rocks, which originate by processes other than "normal" seafloor spreading (Coffin and Eldholm, 1994). Based upon both geochemical (Kempton et al., 2000; Herzberg and O'Hara, 2002; Thompson et al., 2003; Fitton and Godard, 2004; Hastie and Kerr, 2010) and physical and computational modeling (Richards et al., 1989; Campbell and Griffiths, 1990; Farnetani and Richards, 1995; Farnetani et al., 2002; Farnetani and Samuel, 2005; Campbell, 2007) LIPs have been proposed to form by decompression melting of a deep-seated mantle plume. These events occur on a global scale and are found throughout the Earth's history from the Archean to present. Oceanic plateaus are a type of LIP that consist of anomalously thickened oceanic crust on the order of 35 km (e.g. Ontong Java Plateau; Gladczenko et al., 1997; Richardson et al., 2000). These massive outpourings of mafic magmas cover extended areas of the Earth's crust in excess of 1×10^5 km^2 (Saunders et al., 1996). Oceanic plateaus found in the geologic record range in age from ~230 Ma to ~ 90 Ma (Fig. 1) (Greene et al., 2010 and references therein) and have been hypothesized to form over one or more pulses of magmatism that each occurred over a brief period of time (1-3 m.y.) (Duncan, 2002; Coffin et al. 2002; Kerr, 2003). These short intervals of plateau eruption can exceed the production of midocean ridge volcanism for the same period of time (Duncan and Richards, 1991; Larson, 1991). Oceanic plateau eruptions have been linked to multiple Cretaceous oceanic anoxic events, which occurred around the Cenomanian-Turonian boundary (93.5 Ma) and in the early Aptian (~120 Ma)

(Tarduno et al., 1991, 1998; Sinton and Duncan, 1997; Kerr, 1998, 2005; Larson and Erba, 1999; Leckie et al., 2002; Snow et al., 2005). These oceanic anoxic events are characterized by widely distributed organic-rich sediments that are believed to form due to the reduction of dissolved O_2 in the oceans by hydrothermalism associated with oceanic plateau magmatism (Sinton and Duncan, 1997). However, the timing and duration of oceanic plateau magmatism has been a controversial topic (e.g. Ontong-Java Plateau and Wrangellia Plateau) due to the lack of precise geochronological data.

The Ontong-Java Plateau (OJP), located in the Western Pacific (Fig. 1), is the world's largest oceanic plateau. The OJP covers an area of 2.0×10^6 km^2 with crustal thicknesses in excess of 35 km (Gladczenko et al., 1997; Richardson et al., 2000). Geochronological results from samples recovered from ocean drilling and uplifted sections of OJP on the adjacent Solomon Islands indicate a strongly bimodal distribution of ^{40}Ar/^{39}Ar ages at ~122 Ma and ~90 Ma (Mahoney et al., 1993; Tejada et al., 1996, 2002). Castillo et al. (2004) also recognized intermediate ages of ~111-115 Ma, which may suggest lower rates of emplacement for OJP magmatism than previously reported. However, the age and duration of OJP magmatism has not been established with any certainty because the basalts of the OJP have been difficult to date with the ^{40}Ar/^{39}Ar method, due to samples being altered and having very low potassium contents (Fitton et al., 2004). Chambers et al. (2002) even suggests the younger apparent ages (ca. 90 Ma) are the result of argon recoil and represent minimum ages.

The Wrangellia Plateau extends 2500 km within a narrow belt on the western margin of North America from British Columbia to Alaska (Fig. 1) with thicknesses of flood basalts of 6 km (Greene et al., 2010). Samples of Wrangellia flood basalts and plutonic rocks from British Columbia, Yukon, and Alaska have been dated using both U-Pb and ^{40}Ar/^{39}Ar techniques to

yield an age range of ~125-130 Ma (Campbell, 1981; Mortensen and Holbert, 1991; Parrish and McNiccol, 1992; Lassiter, 1995; Bittenbender et al., 2003; Sluggett, 2003; Schmidt and Rodgers, 2007). However, recent $^{40}Ar/^{39}Ar$ geochronological analyses on eight samples of the Wrangellia flood basalts by Greene et al. (2010) only resulted in one sample that retained a magmatic age (227.5 ± 1.2 Ma) that corresponds to previously reported ages of the Wrangellia Plateau. The remaining seven ages ranged from 191-73 Ma and are indicative of open-system behavior of the $^{40}Ar/^{39}Ar$ systematics due to metamorphism.

As seen through previous geochronological studies, difficulties arise when traditional methods are used to date mafic rocks of oceanic plateaus because these rocks are commonly altered and have very low potassium contents. The combination of these factors along with the possible disturbance of $^{40}Ar/^{39}Ar$ ratios due to metamorphism may lead to younger ages being reported than the actual emplacement age of the sample. To overcome the problems of the $^{40}Ar/^{39}Ar$ method, a recently developed in-situ U-Pb SIMS (IN-SIMS) technique by Schmitt et al. (2010) has been utilized to date micro-baddeleyite and micro-zircon from mafic samples. IN-SIMS bypasses the potential problems encountered when mafic rocks are dated with the $^{40}Ar/^{39}Ar$ method by the ability of IN-SIMS to provide precise U-Pb ages. These IN-SIMS ages can then be used to solve fundamental issues that concern oceanic plateaus, such as their age, duration, and environmental implications.

This is a reconnaissance study that tests the application of the IN-SIMS technique on mafic exposures of both oceanic plateau and magmatic arc rocks of the Leeward Antilles within the Caribbean plate. Geochronological age results from this study will provide improved resolution for the temporal evolution of the Caribbean large igneous province (CLIP) and related arcs. If mafic exposures of the Caribbean plate can be successfully dated with the IN-SIMS

technique, then this method can be implemented to precisely date other oceanic plateaus in order to better understand their development within the world's oceans.

Throughout the text, this study uses the time scale of Gradstein et al. (2004) for the ages of the Cretaceous and Paleogene stage boundaries.
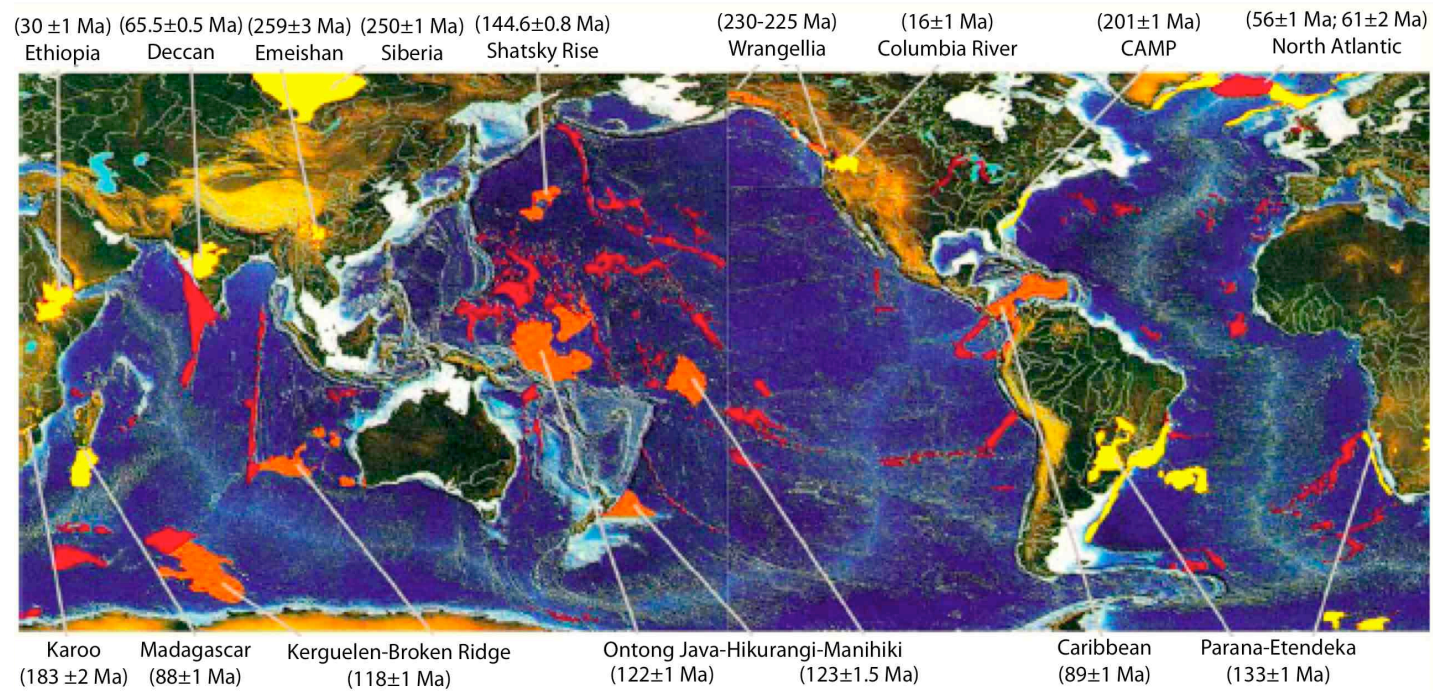
Figure 1: A map that shows the distribution of Phanerozoic large igneous provinces (LIP). LIPs are indicated in yellow (continental) and orange (oceanic) with peak eruption ages. Red areas are flood basalts and ocean islands (modified from Greene et al., 2010 and references therein

CHAPTER 2

CARIBBEAN LARGE IGNEOUS PROVINCE (CLIP)

Bathymetry and geophysical studies indicate that the interior of the Caribbean plate is composed of anomalously thick oceanic crust (Edgar et al., 1971; Diebold et al., 1981; Burke, 1988; Mauffret and Leroy, 1997; Driscoll and Diebold, 1998; Case et al., 1990) that is widely interpreted to be representative of an oceanic plateau (Fig. 1; Caribbean large igneous province; CLIP; also referred to by other workers as the Caribbean-Colombian oceanic plateau; CCOP). CLIP rocks found within the Caribbean, South America, and Central America have been shown lithologically, petrologically, and geochemically to indicate an oceanic plateau origin for the CLIP (Fig. 2; Donnelly, 1973; Donnelly et al., 1990; Kerr et al. 1996; Sinton et al., 1998; White et al., 1999; Revillon et al., 2000; Kerr et al., 2009). Geochronological studies of the CLIP (Fig. 3; Alvarado et al., 1997; Sinton and Duncan, 1997; Sinton et al., 1998; Lapierre et al., 1999; Walker et al., 1999; Revillon et al., 2000) suggest that CLIP magmatism occurred over a short period of time from ca. 92-88 Ma, with a minor pulse of volcanism between ca. 78-72 Ma (Fig. 3; Kerr et al., 1997; Sinton et al., 1998; Revillon et al., 2000). The ~90 Ma pulse of CLIP magmatism represents an enormous outpouring of magmatism as recorded extensively throughout the Caribbean plate. It has also been proposed as a major contributor to the ocean anoxic event that occurred at the Cenomanian-Turonian boundary (Sinton and Duncan, 1997; Kerr, 1988; Kerr et al., 2003; Snow et al., 2005).

In addition to oceanic plateau rocks, fragments of island arc-related sequences are found in the Greater Antilles, Aves Ridge, and Leeward Antilles along the complex accretionary

regions associated with the tectonic margins of the Caribbean plate (Pindell and Dewey, 1982; Pindell and Barrett, 1990; Pindell et al., 2005, 2006). These rocks are thought to be part of a Pacific-derived island arc that formed by subduction of oceanic crust beneath the "Great Arc of the Caribbean" (Beets et al., 1984; Duncan and Hargraves, 1984; Bouysse, 1988; Burke, 1988; White et al., 1999; Kerr et al., 2003; Thompson et al., 2004; Jolly et al., 2006; Pindell et al., 2006). Geochronological results on the island arc rocks of the "Great Arc of the Caribbean" range in age from late Early Cretaceous to Late Cretaceous (Maurasse, 1990; Stockhert et al., 1995; Stanek et al., 2000; Maresch et al., 2000; Pindell et al., 2005).

PREVIOUS STUDIES OF KNOWN OCCURENCES OF THE CLIP

Previous studies of known occurrences of the CLIP indicate that the main characteristics of the CLIP include high-MgO lavas, chemically homogeneous basalts with flat chondrite-normalized REE patterns, lack of a subduction-related trace element signature, pillow lavas that indicate submarine volcanism, low abundance of volcaniclastic deposits, lack of sheeted dyke complexes, and a relatively thick (~5 km) extrusive section (Kerr et al., 2000). Based upon these characteristics, known occurrences of the CLIP have been identified and studied through oceanic drilling, submersible collections, and on-land exposures throughout the Caribbean, South America, and Central America. Known occurrences of the CLIP include DSDP and ODP sites, the Beata Ridge, the Dumisseau Formation and Duarte Complex in Hispaniola, the Bath-Dunrobin Formation in Jamaica, the Leeward Antilles, the Cordillera of western Colombia, the Western Cordillera of Ecuador, the Nicoya Complex of Costa Rica, and the Azuero-Sona Complex in Panama (Fig. 2). In the sections below, key data from these different areas of the CLIP are summarized, except for the Leeward Antilles, which forms the focus of a more detailed later section.

DSDP Leg 15 & ODP Leg 165

DSDP (Deep Sea Drilling Project) Leg 15 at Sites 146, 150, 151, 152, and 153 (Fig. 2; Donnelly, 1973; Donnelly et al., 1973) and ODP (Ocean Drilling Project) Leg 165 at Site 1001 (Fig. 2; Sigurdson et al., 1997; Sinton et al., 2000) sampled the upper ~400-1000 m of the CLIP. These drilled sections consist of thick, coarse-grained, basaltic sills or flows that are overlain by or intrude into limestone (Donnelly et al., 1973). Geochemical analyses of rocks collected by these drilling studies indicate an oceanic plateau affinity (Donnelly et al., 1973; Bence et al., 1975; Sinton et al., 1998; Hauff et al., 2000; Kerr et al., 2002a, 2002b).

Sinton et al. (1998) obtained $^{40}Ar/^{39}Ar$ ages of 90.6 ± 3.2 Ma and 92.1 ± 4.7 Ma for DSDP Leg 15 Site 146 and 94.3 ± 2.8 Ma for DSDP Leg 15 Site 150. These ages are both in agreement with Coniacian sediments that overlie DSDP basalts (Edgar and Saunders, 1973). However, Sinton et al. (1998) consider the age results from DSDP Leg 15 to be imprecise due to low K_2O values and alteration of collected samples. Sinton et al. (2000) reported three $^{40}Ar/^{39}Ar$ ages of basalts that range in age from 80.8-81.3 Ma for ODP Leg 156 Site 1001. This is in agreement with Campanian sediments intercalated within the basalts (Edgar and Saunders, 1973).

Beata Ridge

The Beata Ridge is a topographic structure that trends SSW from Cape Beata in Hispaniola over a distance of 450 km and divides the Caribbean into the Colombia and Venezuela basins (Fig. 2; Fox et al., 1970; Mauffret and Leroy, 1997; Mauffret et al., 2001). Samples of the Beata Ridge were collected by dredging (Fox et al., 1970), drilling during the DSDP Leg 15 (Donnelly et al., 1973), and from the submersible Nautile (Mauffret et al., 2001). The samples consist mainly of gabbros and dolerites, along with rare pillow basalts (Mauffret et

al., 2001). Geochemical analysis of gabbros and dolerites from the Beata Ridge revealed that these samples are similar to basalts collected from DSDP and ODP Sites, as well as other known samples of the CLIP (Revillion et al., 2000).

Revillion et al. (2000) reported ^{40}Ar/^{39}Ar ages that indicate that the predominate age range of both intrusive and volcanic rocks are between 80-75 Ma with a subordinate intrusive phase of 56-55 Ma that has been related to a localized lithospheric thinning event. However, these radiometric ages are inconsistent with the age of intercalated Turonian-Cenomanian sediments that occur within basalts recovered during Nautile studies (Mauffret et al., 2001) and intercalated Turonian-Santonian sediments recovered at DSDP sites of the southern Beata Ridge (Edgar and Saunders, 1973).

The Dumisseau Formation and Duarte Complex

The Dumisseau Formation and the Duarte Complex represent two fragments of oceanic plateau exposed on the island of Hispaniola (Fig. 2; Lewis et al., 1983, 2002; Sen et al., 1988; Draper and Lewis, 1989, 1991; Lewis and Jimenez, 1991; Lapierre et al., 1997, 2000). Many workers have assigned these rocks to the CLIP, based upon both geochemical and petrological analysis (e.g. Sen et al., 1988; Lapierre et al., 1997, 2000; Sinton et al., 1998; Kerr et al., 2003).

The Dumisseau Formation, located in southwestern Haiti (Fig. 2), is divided into an upper and lower unit. Both units consist of pillowed and massive basalts and minor picrites that are interlayered with minor stratified sedimentary layers. The upper and lower units are also locally cut by gabbroic intrusions and dolerite dykes (Maurasse et al., 1979). Sinton et al. (1998) reported five ^{40}Ar/^{39}Ar ages from basalts of the lower unit that range between 88.7 ± 1.5 Ma and 92.0 ± 4.8 Ma. However, paleontological evidence from sediments of the lower unit are possibly early Cretaceous-Cenomanian in age (Maurasse et al., 1979), which does not agree with

radiometric ages obtained by Sinton et al. (1998). There are no direct radiometric age data for

basalts of the upper unit; however, intercalated sediments of Late Campanian age (Maurasse et

al., 1979) and a K-Ar date of a late stage sill that intrudes the upper basalts with an age of 75 ±

1.5 Ma (Sen et al., 1988) suggests that the upper unit is younger than the lower unit. These

upper and lower units are overlain by late Campanian to Maastrichtian limestones (Maurasse et

al., 1979).

The Duarte Complex, located in the Central Cordillera of the Dominican Republic (Fig.

2), is divided into an upper and lower unit (Palmer et al., 1979). The lower unit consists of

massive and banded picrites and basalts that are locally capped by breccias and intruded by

synvolcanic dikes and sills of basalt and dolerite (Escouder-Viruete et al., 2007). The upper unit

consists of a massive and homogeneous pile of basaltic submarine flows with sparse interlayered

carbonate pelagic sediments, and rare intrusions of synvolcanic mafic dikes (Escouder-Viruete,

2007). The picrites and high-Mg basalts are chemically related to plume magmas (Draper and

Lewis, 1991; Lewis and Jimenez, 1991). A geochronological study by Lapierre et al. (1999)

obtained ^{40}Ar/^{39}Ar amphibole ages of 86.1 ± 1.3 Ma for a picrite and 86.7 ± 1.6 Ma for an

amphibolite. However, Lewis et al. (1999) argue that these ages are due to thermal effects

associated with metamorphism and do not represent the primary crystallization age of the Duarte

Complex. In an effort to further constrain the timing of tectonometamorphism of the Duarte

Complex, Escouder-Viruete et al. (2007) reported two ^{40}Ar/^{39}Ar ages from amphibolites of 93.9

± 1.4 Ma and 95.8 ± 1.9 Ma. Escouder-Viruete et al. (2007) propose that the protoliths of the

amphibolites must be older than the reported Cenomanian ^{40}Ar/^{39}Ar ages due to metamorphism.

This hypothesis is consistent with a Sm/Nd isochron age of 115 ± 20 Ma obtained from eight

samples of picrites and high-Mg basalts of the Duarte Complex (Escuder-Viruete et al., 2004)

and Albian to Upper Cenomanian fossils found within the overlying Tiero Formation

(Montgomery and Pessagno, 1999).

Bath-Dunrobin Formation

The Bath-Dunrobin Formation is located within Jamaica (Fig. 2) and consists of a thick

sequence of late Cretaceous extrusive, tholeiitic, massive basalts that occur with intercalated

island arc tuffs (Hastie et al., 2008). The Bath-Dunrobin lavas are exposed as two fault bounded

blocks that cover an area of 40 km^2 (Wadge et al., 1982). Based on major element and limited

trace elemental data, Jackson et al. (1980) and Jackson (1987) concluded that the Bath-Dunrobin

lavas have a MORB affinity. However, other studies have shown that the Bath-Dunrobin lavas

are similar to samples of DSDP Leg 15 (e.g. Wadge and Draper, 1978; Wadge et al., 1982) and

are more likely representative of the CLIP (Donnelly et al., 1990; Kerr et al., 2003; Hastie et al.,

2008). There are no available radiometric ages for the Bath-Dunrobin Formation; however,

Hastie et al. (2008) concluded that the Bath-Dunrobin Formation is likely Turonian-Coniacian in

age based upon the ages of radiolarian found within interbedded red cherts and mudstones

(Montgomery and Pessagno, 1999). The Bath-Dunrobin Formation is overlain by a thick

sequence of Maastrichtian volcaniclastic rocks (Wadge et al., 1982)

The Central Cordillera, Western Cordillera, and Serriano de Baudo of Colombia

In western Colombia, mafic rocks outcrop into three north-south trending, fault-bounded

belts that are named (from east to west) the Central Cordillera, Western Cordillera, and Serriano

de Baudo. These three terranes in western Colombia have been shown to be geochemically

consistent with derivation from an oceanic plateau and linked to the CLIP (Marriner and

Millward, 1984; Millward et al., 1984; Nivia, 1987; Storey et al., 1991; Kerr et al., 1996, 1997,

2002, 2003). Most authors agree that these allochthonous belts were accreted to the South

American margin in the Late Cretaceous or early Tertiary (e.g. McCourt et al., 1984; Millward et al., 1984; Bourgois et al., 1987).

The Central Cordillera consists of Cretaceous massive and pillowed picritic to tholeiitic basalts with some ultramafic cumulates (McCourt et al., 1984; Spadea et al., 1989). These mafic rocks occur in several discontinuous lenses and are bounded to the east by the Romeral fault, which separates continental crust from oceanic crust (Case et al., 1973). $^{40}Ar/^{39}Ar$ ages were obtained from picrites of the Central Cordillera and these yield ages of 93.21 ± 3.60 Ma and 88.95 ± 3.27 Ma (Kerr et al., 2002b). However, these ages are not in agreement with a Rb-Sr isochron age of 99 ± 4 Ma obtained from a cross-cutting arc-related intrusion of the Buga batholith (McCourt et al., 1984).

The Western Cordillera is separated from the Central Cordillera by the Cauca-Patia graben and separated from the Serriano de Baudo by the San Juan Atrato trough (Kerr et al., 1997). The Western Cordillera consists of tectonic slices of pillowed and massive basalts, dolerites, local gabbros, and rare tuffs that are separated by steeply dipping fault-bounded lenses of metasediments (Barrero, 1979; Aspden, 1984). Basalts of the Western Cordillera were dated by $^{40}Ar/^{39}Ar$ methods and yield two distinct ages of 91.7 ± 2.7 Ma and 76.5 ± 1.6 Ma (Kerr et al., 1997; Sinton et al., 1998). The ~92 Ma radiometric ages are consistent with Cenomanian-Turonian and Turonian-Coniacian ages from intercalated sediments (Bourgois et al., 1987; Barrerro, 1979). Early Tertiary subduction related volcanics occur on the western periphery of the Western Cordillera (Tistl and Slazar, 1994) and have $^{40}Ar/^{39}Ar$ ages of 43.1 ± 0.4 Ma (Sinton, 1996).

The Serrania de Baudo is the westernmost mafic belt and crops out along the northwest Pacific coast of Colombia (Goossens et al., 1977; Macia, 1985; Kerr et al., 2002b). It consists of

pillowed and massive basalts with some basaltic breccias, dolerites and gabbros (Goossens et al., 1977; Macia, 1985). $^{40}Ar/^{39}Ar$ analyses from Serrania de Baudo basalts yield ages of 72.3 ± 0.4 Ma and 77.9 ± 1.0 Ma (Kerr et al., 1997), which are consistent with Upper Cretaceous bivalves found within the basalts by Gansser (1973). This unit is overlain by a poorly exposed sequence of subduction related basalts that are intercalated with Eocene limestones (Gansser, 1973).

Western Cordillera of Ecuador

The Western Cordillera of Ecuador consists of multiple allochthonous oceanic blocks that were accreted to the South American margin from the Late Cretaceous to Eocene (Goosens and Rose, 1973; Feininger and Bristow, 1980; Kerr et al., 2002; Jaillard et al., 2004; Pratt et al., 2005; Spikings et al., 2005; Luzieux et al., 2006; Vallejo et al., 2006). The San Juan, Guaranda, and Pinon terranes (from east to west) are located in the Western Cordillera of Ecuador. These terranes have been shown to be both petrologically and geochemically consistent with an oceanic plateau origin, and are interpreted to be parts of the CLIP (Kerr et al., 1996, 2002; Reynaud et al., 1999; Lapierre et al., 2000; Pourtier, 2001; Mamberti et al., 2003, 2004; Vallejo et al., 2009).

The San Juan terrane (eastern part of the Pallatanga terrane of McCourt et al., 1998; Kerr et al., 2002) outcrops in a narrow belt at the eastern border of the Ecuadorian Western Cordillera and consists mostly of ultramafic rocks that include peridotites, layered cumulates, and gabbros (Mamberti et al., 2004). Lapierre et al. (2000) obtained a Sm-Nd isochron of 123 ± 13 Ma from a gabbro thought to be within the San Juan terrane. However, Vallejo et al. (2009) suggest that the age obtained from Lapierre et al. (2000) may be due to erroneous mapping and speculated that the dated sample is actually part of the Peltec unit, which is part of an arc related sequence that was accreted to the South American margin in the Aptian (Litherland et al., 1994). Mamberti et al. (2004) also obtained a poor $^{40}Ar/^{39}Ar$ integrated age from a gabbro within the

San Jaun Terrane of 105 Ma. A more recent U-Pb SHRIMP age of 87.10 ± 1.66 Ma was determined from extracted zircons within a layered gabbro of the San Juan terrane (Vallejo et al., 2006; Vallejo, 2007). The San Juan Terrane is overlain by a turbiditic sequence, known as the Yunguillla Formation, of Early Maastrichtian age and these strata are interpreted to postdate the accretion of the San Juan terrane to the South American margin (Bristow and Hoffstetter, 1977; Jaillard et al., 2004). A Late Campanian age of accretion of the San Juan terrane is therefore established due to the stratigraphic relationship of the San Juan terrane with the Early Maastrichtian Yunguillia Formation (Hughes and Pilatasig, 2002; Kerr et al., 2002; Jaillard et al., 2004, 2008, 2009).

The Guaranda terrane (western part of the Pallatanga terrane of McCourt et al., 1998; Kerr et al., 2002) is located to the west of the San Juan terrane and these two terranes are separated by a major fault (Hughes and Pilatasig, 2002; Jaillard et al., 2009). The Guaranda terrane consists of hyaloclastics, pillow basalts, dolerites, gabbros, high-Mg basalts, ankaramites, and picrites (Mamberti et al., 2003). Although there are no direct geochronological data for the Guaranda terrane, it is overlain by either pelagic cherts that yield Santonian-Maastrichtian radiolaria (Boland et al., 2000) or the 85-72 Ma lavas and volcaniclastic products of the Rio Cala island arc (Luzieux et al., 2006; Vallejo et al., 2006, 2009). These relations suggest a Late Cretaceous age for the Guaranda terrane. The latest Cretaceous oceanic cherts are unconfomably overlain by micaceous quartz-sandstones of Early and Middle Paleocene age (Hughes et al., 1998). The abrupt arrival of the quartz-sandstones are interpreted to be the result of the accretion of the Guaranda terrane to the South American margin, which occurred in the Middle to Late Maastrichtian (Jaillard et al., 2004).

The Pinon terrane is located in the coastal area of the Western Cordillera and consists of basalts, pillow basalts, dolerites, and small gabbroic intrusions (Jaillard et al., 2009). ^{40}Ar/^{39}Ar analyses from Pinon basalts yielded an age of 88 ± 1.6 Ma (Luzieux et al., 2006; Luzieux, 2007). The Pinon basement is overlain by a thick series of andesitic breccias, tuffs, and basaltic lavas that are then overlain by black siliceous limestones of Coniacian age (Reynaud et al., 1999). Jaillard et al. (2009) proposed a Late Paleocene age for the accretion of the Pinon terrane to the South American margin based upon the unconformable deposition of quartz-rich deposits of latest Paleocene age within the Pinon terrane. These quartz-rich deposits are interpreted to represent the arrival of continent-derived sediments from South America (Jaillard et al., 1995; Boland et al., 2000; Deniaud, 2000)

The Nicoya Complex

The Nicoya Complex is a tectonic block located within the Nicoya Peninsula of Costa Rica at the southwestern edge of the Chortis block (Fig. 2; Hauff et al., 2000). It consists of massive and pillowed basalts, volcanic breccias, dolerites, gabbros, plagiogranite intrusives, hyaloclastites, cherts, and limestones (Dengo, 1962; Kuijpers, 1980) and is widely believed to be part of the CLIP based upon its geochemical similarity to other known rocks of the CLIP (Donnelly, 1994; Sinton et al., 1997; Hauff et al., 2000; Hoernle et al., 2004; Denyer et al., 2006; Denyer and Gazel, 2009). Multiple ^{40}Ar/^{39}Ar geochronological studies have been conducted on the Nicoya Complex and these data suggest an age range of ~50 m.y. Sinton et al. (1997) and Hauff et al. (2000) obtained ages that ranged from 84-83 Ma for intrusives and 95-88 Ma for basalts of the Nicoya Complex. However, Hoernle et al. (2004) reported two separate age ranges for basalts of 119-111 Ma and 139-133 Ma, which are significantly older than previous geochronological studies. Two facies of ribbon radiolarian cherts are intercalated within the

Nicoya Complex and yield paleontological ages: Fe-radiolarites with a Coniacian-Santonian age and Mn-radiolarites with a Bajocian to Albian age (Kuijpers, 1980; Baumgartner, 1984; Denyer and Baumgartner, 2006). The age of the Fe-radiolarites (Coniacian-Santonian) are largely synchronous with the earlier radiometric ages reported by Sinton et al. (1997) and Hauff et al. (2000). However, the age of the Mn-radiolarites (Bajocian-Albian) are inconsistent with reported $^{40}Ar/^{39}Ar$ ages of the Nicoya Complex because there has not been any Middle Jurassic basement found in the Nicoya Complex. The Nicoya Complex is overlain by Upper Cretaceous sediments (~75 Ma) from the Central American arc, which provide a minimum age for this complex (Hauff et al., 1997).

Azuero-Sona Complex

The Azuero-Sona Complex is located within the Azuero and Sona Peninsulas of the Pacific margin of southwestern Panama (Fig. 2; Goosens et al., 1977). The basement of the Azuero-Sona complex consists of rocks that range from highly tectonized and metamorphosed basalts to relatively undeformed pillow basalts (Del Giudice and Recchi, 1969; Metti and Recchi, 1972; Krawinkel et al., 1999). Based upon geochemical and petrological characteristics, the basement rocks of the Azuero-Sona Complex are similar to that of the Nicoya Complex and are inferred to represent part of the CLIP (Wildberg et al., 1984; Hauff et al., 1997, 2000; Sinton et al., 1997, 1998; Hoernle et al., 2002, 2004; Kerr et al., 2003, Worner et al., 2009). The Azuero Peninsula yields $^{40}Ar/^{39}Ar$ ages of basalts between 66 to 50 Ma (Hoernle et al., 2002). The Sona Peninsula basalts are slightly older based upon $^{40}Ar/^{39}Ar$ geochronological studies by Hoernle et al. (2002) and Hoernle and Hauff (2007) indicating an age of 71 ± 2 Ma for one analyzed grain. These older ages are consistent with the paleontological age of the Ocu Formation (Upper Cretaceous; Del Giudice and Recchi, 1969), which unconformably overlies the Azuero-Sona

Complex. However, the younger ages from the Azuero Peninsula are inconsistent with the fossil ages of the Ocu Formation.

Summary of known CLIP occurrences

Geochronological studies of known occurrences of the CLIP from oceanic drilling, submersible collections, and on-land exposures result in an age range of ~90 m.y. for the CLIP (Fig. 3; Table 1; 139-50 Ma; Berriasian-Ypresian). The majority of the ages obtained within these studies do occur within the ~88-92 Ma interval that is seen widespread throughout the CLIP by previous geochronological studies (Fig. 3; Table 1; e.g. Alvarado et al., 1997; Sinton and Duncan, 1997; Sinton et al., 1998; Lapierre et al., 1999; Walker et al., 1999; Revillon et al., 2000). However, due to the extensive duration of CLIP magmatism (~90 m.y.), previous interpretations for the formation of the CLIP within a short interval of time (1-3 m.y.) should be reevaluated (e.g. Sinton et al., 1998; Kerr et al., 2003).

The accuracy of ages obtained within these studies should also be reexamined. The majority of the geochronological data from the CLIP were analyzed with the $^{40}Ar/^{39}Ar$ method (Fig. 3; Table 1). As discussed earlier, the $^{40}Ar/^{39}Ar$ method can result in imprecise ages when geochronological data is obtained for oceanic plateau rocks because these rocks are commonly altered and contain low potassium contents. Another important concern is the disagreement between $^{40}Ar/^{39}Ar$ radiometric data from the CLIP with paleontological evidence that is overlain/intercalated with CLIP occurrences (Table 1).   These discrepancies provide doubt in the validity of ages reported when the $^{40}Ar/^{39}Ar$ technique is used.

Table 1: Data from Known Occurrences of the CLIP. See figure 2 for CLIP locations. All ages shown are from [40]Ar/[39]Ar analyses, unless noted by the symbol # representing U-Pb zircon analysis and * representing IN-SIMS analysis. Data that is red in color indicates geochronological data that is inconsistent with either intercalated or overlying sediments. Geologic time scale from Gradstein et al., 2004.

Geologic time scale (left column):

Era	Period	Epoch	Stage	Age (Ma)
Paleogene		Oligocene	Chattian	23.03
			Rupelian	28.4
		Eocene	Priabonian	33.9
			Bartonian	37.2
			Lutetian	40.4
			Ypresian	48.6
		Paleocene	Thanetian	55.8
			Selandian	58.7
			Danian	61.7
				65.5
Cretaceous	Late		Maastrichtian	70.6
			Campanian	
			Santonian	83.5
			Coniacian	85.8
			Turonian	89.3
			Cenomanian	93.5
	Early		Albian	99.6
			Aptian	112.0
			Barremian	125.0
			Hautervian	130.0
			Valanginian	136.4
			Berriasian	140.2
				145.5
Jurassic	Late		Tithonian	150.8
			Kimmeridgian	155.7
			Oxfordian	161.2
	Middle		Callovian	164.7
			Bathonian	167.7
			Bajocian	171.6

Location	Age (Ma)	Intercalated Sediments	Overlying Sediments
DSDP Leg 15 Site 146	90.6 - 92.1	N/A	Coniacian (89.3 - 85.8)
DSDP Leg 15 Site 150	94.3 ± 2.8	N/A	Coniacian (89.3 - 85.8)
ODP Leg 156 Site 1001	80.8 - 81.3	N/A	Campanian (83.5 - 70.6)
Beata Ridge	80 - 75 56-55	Cenomanian - Turonian (99.6 - 89.3) Turonian-Santonian (93.5 - 83.5)	Mid Eocene (48.6 - 40.4)
Dumisseau Formation			
Lower	92 - 88	Early Cretaceous-Cenomanian (112.0 - 93.5)	Campanian-Maastrichtian (83.5 - 65.5)
Upper	N/A	Late Campanian (75 - 70.6)	Campanian-Maastrichtian (83.5 - 65.5)
Duarte Complex	96 - 86	N/A	Albian - Upper Cenomanian (112 - 96)
Bath-Dunrobin Fm	N/A	Turonian - Coniacian (93.5 - 85.8)	Maastrichtian (70.6 - 65.5)
Colombia			
Central	93.2 - 89.0	N/A	Paleogene (65.5 - 23.03)
Western	91.7 ± 2.7 76.5 ± 1.6	Cenomanian - Turonian (99.6 - 89.3) Turonian - Coniacian (93.5 - 85.8)	Paleogene (65.5 - 23.03)
Serriano de Baudo	77.9 - 72.3	Upper Cretaceous	Eocene (55.8 - 33.9)
Ecuador			
San Juan	105 87.0 ± 1.66[#]	N/A	Early Maastrichtian (70.6 - 65.5)
Guaranda	N/A	N/A	Santonian - Maastrichtian (85.8 - 65.5)
Pinon	88.6 ± 1.6	N/A	Coniacian (89.3 - 85.8)
Nicoya Complex	95 - 88 139-133 119-111 84-83	Bajocian - Albian (171.6 - 99.6) Coniacian - Santonian (89.3 - 83.5)	Upper Cretaceous
Azuero-Sona Complex	66-50 71 ± 2	N/A	Upper Cretaceous
Aruba Lava Formation	99.4 ± 4.5*	Turonian (93.5 - 89.3)	Eocene (55.8 - 33.9)
Curacao Lava Formation	89.5 ± 1.0 88.0 ± 1.2 114.7 ± 7.4*	Albian (112 - 99.6)	Santonian (85.8 - 83.5)
Gran Roque Gabbro	87.0 ± 4.1*	N/A	Neogene (23.03 - 0)
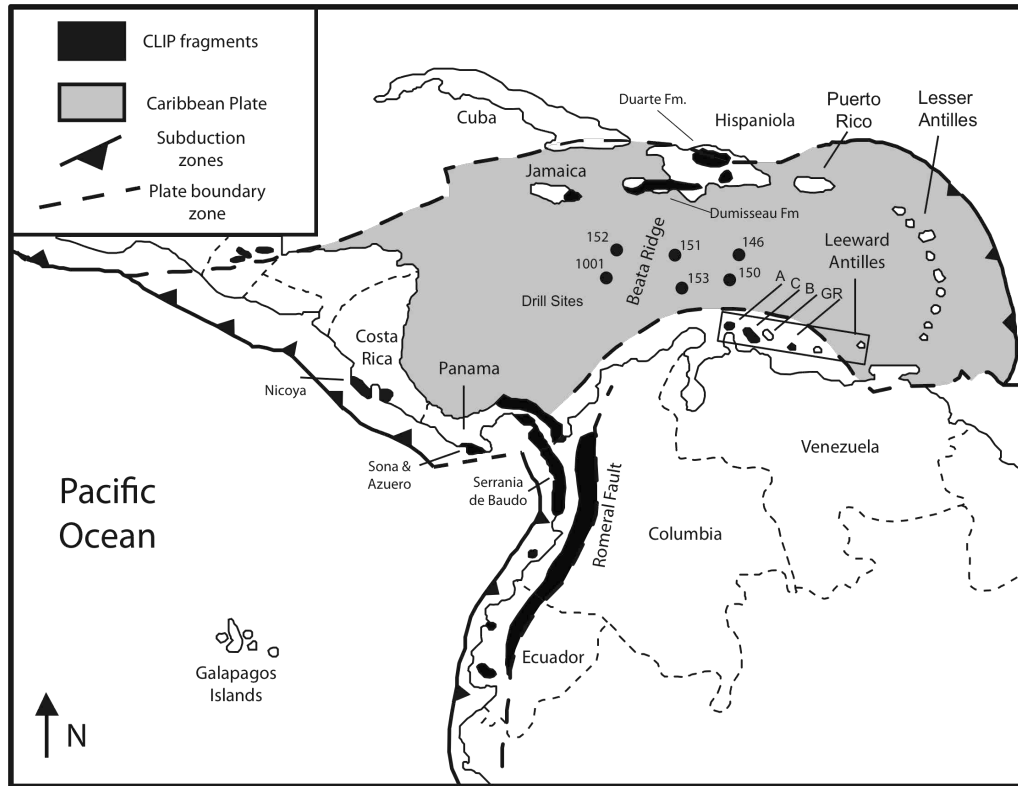
Figure 2: A map that shows the extent of the Caribbean plate and locations of on land CLIP fragments within the Caribbean, Central America, and South America. Abbreviations are as follows: A (Aruba), C (Curaçao), B (Bonaire), GR (Gran Roque) (modified from Kerr et al., 2003).
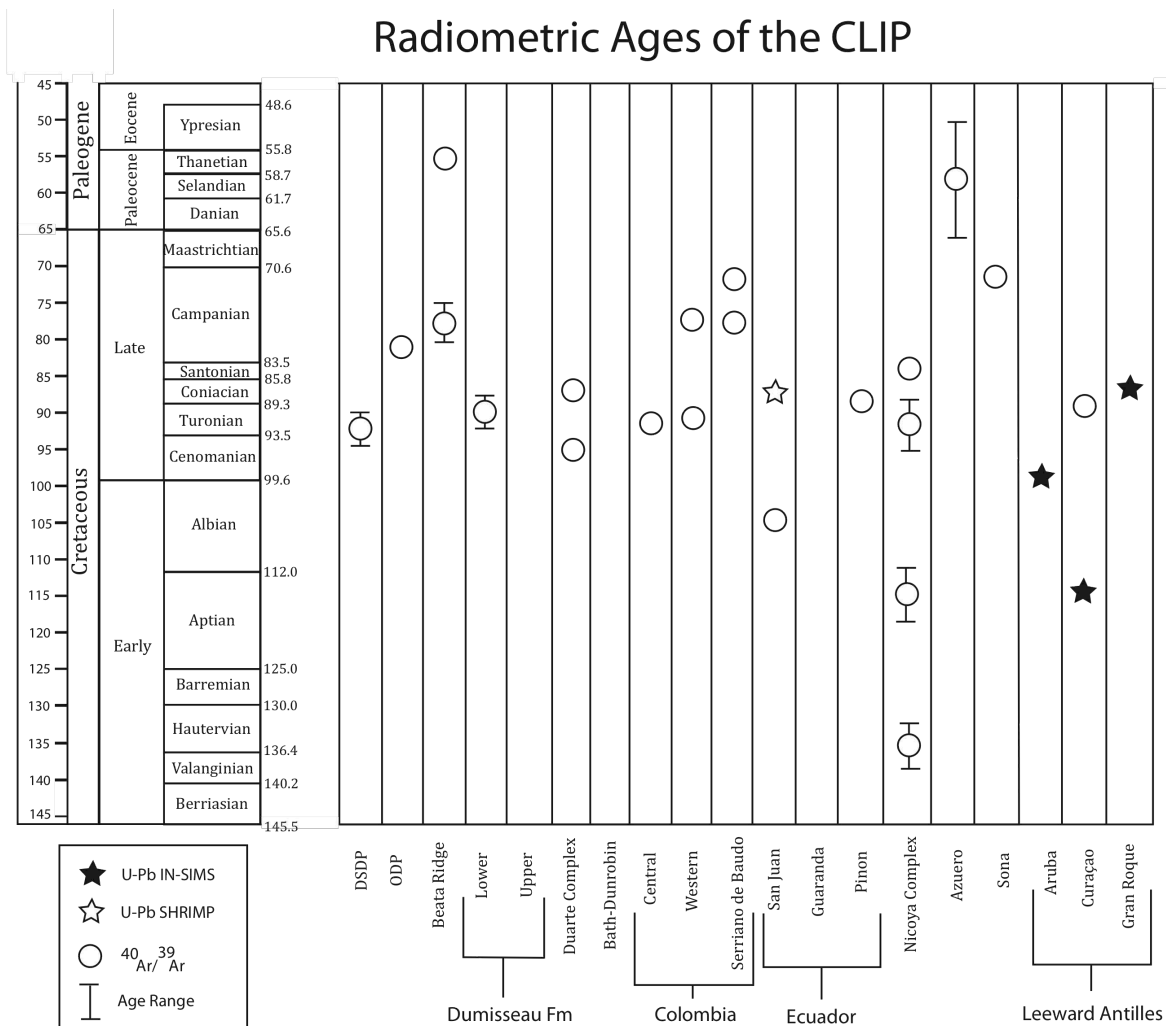
Figure 3: A graphical display of radiometric ages of known CLIP occurrences from the Caribbean, Central America and South America. The black stars represent IN-SIMS ages, the white stars represent U-Pb SHRIMP ages, the open circles represent $^{40}Ar/^{39}Ar$ ages, and the brackets represent an age range for multiple analyses. Geologic time scale from Gradstein et al., 2004.

CHAPTER 3

NEW IN-SIMS STUDIES IN THE LEEWARD ANTILLES

The Leeward Antilles represent isolated exposures of a submarine ridge that extends from Aruba on the west to La Blanquia on the east that trends parallel to the transpressional Caribbean-South American plate boundary zone in a WNW-ESE direction (Fig. 2; Beardsley and Ave Lallemant, 2007). The Leeward Antilles islands of Aruba, Curacao, Bonaire, and Gran Roque were chosen to test the application of the IN-SIMS technique. These islands are ideal for geochronological studies within the Caribbean plate because they contain on-land exposures of both the CLIP and Cretaceous magmatic arc assemblages that have been tectonically uplifted along the South American continental margin (Beets et al., 1984; White et al., 1999; Kerr et al., 2003; Thompson et al., 2004). Exposures on these islands allow for lower sections of the magmatic sequence to be sampled in order to gain a full perspective on magmatic processes that occur within the Caribbean plate. These islands have also been recently remapped in detail to provide accurate field relations for each island (e.g. Wright and Wyld, 2004, 2010). Another benefit for new geochronological studies is that various age dating techniques have been utilized in prior studies that allow for comparison between these previous methods and new IN-SIMS age results. These previous studies also indicate discrepancies between previous age determinations and paleontological evidence (Table 1) that suggests that there may be problems with the accuracy of previous geochronological data from the Leeward Antilles.

This study utilizes the IN-SIMS technique on both oceanic plateau and arc magmatic rocks of the Leeward Antilles islands of Aruba, Curacao, Bonaire, and Gran Roque (Fig. 2). The

IN-SIMS technique will provide U-Pb ages that bypass the potential problems encountered when using the $^{40}Ar/^{39}Ar$ method to date mafic rocks. This improved resolution in geochronological data will provide insights into the temporal evolution of both the CLIP and related arcs of the Leeward Antilles.

In the following sections, an overview of the regional geology for Aruba, Curaçao, Bonaire, and Gran Roque will be presented, with an in-depth description of each unit in which samples were collected for IN-SIMS geochronology. Discussion of previous geochronological studies and paleontological evidence will also be addressed to compare with new IN-SIMS results from this study.

ANALYTICAL METHODS

Hand-sample sized samples were collected from the Leeward Antilles islands of Aruba, Curacao, Bonaire, and Gran Roque (Fig. 2). These samples were collected at localities with minimal degrees of weathering and where clear contact relations with other units are present. Samples were stored in sealed plastic and fabric bags in order to prevent any contamination by mixing with other samples, dirt, or dust. Polished thin sections were then prepared from each of the samples. One polished thin section was used for IN-SIMS analysis from each of the Leeward Antilles islands of Aruba, Curacao, Bonaire, and Gran Roque.

Polished thin sections of collected samples were analyzed by a microprobe at the University of Wyoming, which used x-ray mapping of zirconium and back-scattered electron (BSE) imaging. Potential zirconium targets were then differentiated by electron dispersive spectrometry (EDS) to determine if the grains were zircon, baddeleyite, or another mineral. Images of potential targets were taken under varying magnifications (40x, 300x, and 2000x) with BSE to locate these grains under reflected light (Fig. 4A). These targets were then found in

reflected light and images were taken under various magnifications (10x, 20x, and 40x objective lenses) (Fig. 4B). The 40x images in reflected light are comparable in scale to the 2000x BSE images.

Potential target regions of the polished thin sections were cut out and mounted on an epoxy disk along with previously polished zircon and baddeleyite standards (Fig. 4C). These mounts were then gold-coated for conductivity purposes. Images were taken of the gold-coated mounts under varying magnifications (10x, 20x, 40x objective lenses) for identification while using the SIMS (Fig. 4D).

The CAMECA ims1270 SIMS at UCLA was used to conduct the in-situ U-Pb SIMS (IN-SIMS) technique. Due to the small size (<10 um) of target grains, a field aperture was utilized in order to block secondary ions emitted from host phases. Analyses consisted of seven cycles for standards and 15 to 30 cycles for zircon and baddeleyite targets. Each cycle measured counts of 203.5 (background), $^{94}Zr_2O^+$, $^{204}Pb^+$, $^{206}Pb^+$, $^{207}Pb^+$, $^{208}Pb^+$, $^{232}Th^+$, $^{238}U^+$, $^{238}UO^+$, and $^{238}UO_2^+$. Pb/U instrumental fractionation of the unknowns were corrected by $^{206}Pb/^{238}U$ relative sensitivity vs. UO_2^+/U^+ calibrations. Data reduction and error calculations used UCLA in-house software ZIPS version 3.1.4. A detailed explanation of operating conditions for IN-SIMS U-Pb analysis is described in Schmitt et al. (2010).

ARUBA

The basement of Aruba consists of the Late Cretaceous Aruba Lava Formation (ALF) and cross-cutting 89 ± 1 Ma Aruba batholith, which are unconformably overlain by Eocene limestones and younger strata (Fig. 5; Westermann, 1932; Beets and MacGillavry, 1977; Helmers and Beets, 1977; Monen, 1977; Beets et al., 1984, 1996; Jackson and Robinson, 1994; White et al., 1999; Wright and Wyld, 2004, 2010).

The Aruba Lava Formation (ALF)

The ALF is located within the central part of Aruba and covers an area of approximately 20 km^2, truncated at the northeastern side by the Caribbean Sea and elsewhere by the composite Aruba batholith (Fig. 5; Beets et al., 1984, 1996). Beets et al. (1984) described the ALF as a sequence of weakly metamorphosed mafic lavas, diabase, and pyroclasitc and volcaniclastic sediments. Snoke et al. (2001) performed geochemical analysis on samples from the ALF and concluded that the lavas represent an island arc succession. However, based upon the presence of high-MgO lavas, the absence of a subduction related trace-element signature, and the chemical similarity to other analyzed samples of the CLIP, most authors now agree that the ALF represents a fragment that belongs to the CLIP (e.g. Kerr et al., 1997, 2003; Sinton et al., 1998; White et al., 1999; Wright and Wyld, 2004, 2010).

The ALF has been interpreted by previous mapping studies to be an unbroken stratigraphic succession intruded by diabase sills at all levels (Beets et al., 1984, 1996). However, recent mapping by Wright and Wyld (2010) identified an angular unconformity that separates the ALF into two separate stratigraphic packages, and these are referred to as the upper and lower ALF (Fig. 5). The following summary of geological relations on Aruba is taken from Wright and Wyld (2010), except where noted otherwise.

The lower ALF is divided into three mappable units: the basalt, argillite, and diabase units (Fig. 5). The basalt unit consists mostly of pillowed and massive basalt flows with rare layers of associated volcaniclastic strata. The overlying argillite unit is composed mostly of thinly bedded argillite with less common volcaniclastic strata. Ammonites have been found in strata of the argillite unit that indicate a Turonian age (Fig. 5; MacDonald, 1968). The basalt and

argillite units are both intruded by a complex assemblage of texturally variable dikes, sills, and small intrusions that make up the diabase unit.

The upper ALF consists of a locally preserved basal unit of basaltic tuffs and an overlying polymictic conglomerate that overlie the lower ALF along an angular unconformity (Fig. 5). The tuff unit consists of well-bedded accretionary lapilli tuff that is locally dominated by tuff breccias. The conglomerate unit consists of a well-rounded pebble to cobble polymictic conglomerate, in which clasts are derived entirely from lower units. Wright and Wyld (2010) conclude that the unconformity between the upper and lower ALF represents a period of uplift and erosion, and marks a distinct transition from marine deposition to subaerial conditions.

White et al. (1999) attempted to obtain $^{40}Ar/^{39}Ar$ ages from the ALF, however the Ar systematics of the samples were too disturbed for reliable age results to be determined. However, the age of the ALF is constrained by the presence of a Turonian fossil found within sedimentary intercalations of the lower ALF (MacDonald, 1968) and the cross-cutting 89 ± 1 Ma Aruba batholith (Wright and Wyld, 2010).

Deformation, Metamorphism, and Plutonism

Previous work attributed deformation and metamorphism of the ALF to the intrusion of the Aruba batholith (Westermann, 1932; Monen, 1977; Beets et al., 1984, 1996; White et al., 1999), which has been dated at 89 ± 1 Ma (U-Pb zircon; Wright and Wyld, 2010). Recent mapping and structural studies, however, indicate that deformation (folds and foliation) and metamorphism (subgreenshchist grade) is regional in the ALF and not spatially associated with the Aruba batholith (Wright and Wyld , 2010). In addition, deformation structures are cut discordantly by dikes associated with the Aruba batholith and are overprinted by contact metamorphism in a narrow zone around the batholith (Wright and Wyld, 2010). These relations

led Wright and Wyld (2010) to conclude that the Aruba batholith emplacement postdates the regional deformation of the ALF.

IN-SIMS Results from the ALF

Samples were collected from the diabase unit of the lower ALF (see figure 5 for sample location). The mineralogy of the diabase consists of plagioclase + actinolite + clinopyroxene + epidote + chlorite + quartz + opaques (Figs. 6A & 6B). Ages of nine baddeleyite analyses yielded a mean age of 101.8 ± 8.5 Ma (95% conf.) (Fig. 7A). Six zircon analyses yielded a mean age of 97.3 ± 5.2 Ma (95% conf.) (Fig. 7B). A mean age of both the baddeleyite and zircon analyses resulted in an age of 99.4 ± 4.5 Ma (95% conf.). The mean age of 99.4 ± 4.5 Ma from both baddeleyite and zircon analyses is considered to be representative of the age of the diabase unit of the lower ALF because the resultant ages of the baddeleyite and zircon analyses overlap within error.

Implications for IN-SIMS Results from the ALF

An IN-SIMS age of 99.4 ± 4.5 Ma was determined for the diabase unit of the ALF from both nine baddeleyite and six zircon analyses. This age for the diabase unit of the ALF is slightly older than a Turonian fossil found within the lower ALF (Fig. 5; MacDonald, 1968) and indicates that the ALF is at least Cenomanian in age.

CURAÇAO

The basement of Curaçao consists of the Cretaceous Curaçao Lava Formation (CLF) that is overlain unconformably by the Late Cretaceous to Early Paleocene Knip Group and Midden-Curaçao Formation (Fig. 8; Beets, 1972; Klaver, 1976; Beets et al., 1977; Wright and Wyld, 2004, 2010). These rocks are then unconformably overlain by Eocene limestone and younger strata (Fig. 8).

The Curaçao Lava Formation (CLF)

The CLF is a 5 km thick succession that covers most of Curaçao, and consists of predominantly picritic to basaltic pillow lava flows with minor reworked hyaloclastites and some diabasic sills and dikes (Fig. 8; Beets et al., 1984; Klaver, 1987). Kerr et al. (1996) showed that the picrites of the CLF are related to the basalts by simple fractional crystallization of olivine, clinopyroxene, and plagioclase. As shown by multiple authors, CLF lavas show a similarity in major and trace element chemistry to other samples of the CLIP, especially the ALF (e.g. Donnelly and Rogers, 1978; Beets et al., 1982, 1984; Donnelly et al., 1990; Kerr et al., 1996; Sinton et al., 1998; White et al., 1999).

Early geochronological studies by Santamaria et al. (1974) reported two K-Ar analyses of whole rock dolerites collected within the CLF with ages of 118 ± 10 Ma and 126 ± 12 Ma. A more recent investigation by Sinton et al. (1998) obtained two whole rock $^{40}Ar/^{39}Ar$ analyses that yielded plateau ages of 89.5 ± 1.0 Ma and 88.0 ± 1.2 Ma for CLF basalts collected at the base and top of the CLF, respectively. However, these $^{40}Ar/^{39}Ar$ ages are not consistent with an Albian ammonite found in a pelagic interval of the CLF (Fig. 8; Weidman, 1978). Kerr et al. (2003) argue that the ammonites may be reworked or misidentified due to the condition of the fossils being poorly preserved, incomplete, and distorted. However, Snoke et al. (2001) maintain the ammonites accurately reflect the age of the CLF and volcanism began in the Albian. A minimum age can be concluded for the CLF lavas based upon the 86.2 ± 0.8 Ma age determined for a diorite dike that intrudes the CLF (U-Pb Zircon; Wright and Wyld, 2004).

Deformation and Metamorphism

Curaçao was affected by a single phase of regional deformation and metamorphism that affected all units older than the Eocene, including the Midden-Curaçao Formation (Beets, 1972).

Beets (1972) and Klaver (1987) described this Paleocene event to be characterized by NW-trending folds on both the outcrop and map-scale where they control the map pattern of bedrock units. Wright and Wyld (2010) reported that mineral assemblages indicate that metamorphism occurred at a phrenite-pumpellyite to zeolite grade.

IN-SIMS Results from the CLF

Samples were collected from diabase within the CLF (see figure 8 for sample location). The mineralogy of the diabase consists of plagioclase + actinolite + clinopyroxene + opaques (Figs. 9A & 9B). Ages of eight baddeleyite analyses yielded a mean age of 114.7 ± 7.4 Ma (95% conf.). One zircon analysis yielded an age of 102 ± 6 Ma (95% conf.). A mean age of both baddeleyite and zircon analyses yield an age of 112.7 ± 7.3 Ma (95% conf.) (Fig. 10). An age of 114.7 ± 7.4 Ma from baddeleyite analyses is considered to be representative of the age of the diabase within the CLF because only one zircon grain was analyzed and the age was considerably younger than the eight analyzed baddeleyite grains.

Implications for IN-SIMS Results from the CLF

IN-SIMS analyses of diabase within the CLF yielded an age of 114.7 ± 7.4 Ma from eight baddeleyite analyses. This Aptian age is significantly older than previously reported Turonian-Coniacian $^{40}Ar/^{39}Ar$ ages (ca. 89-90 Ma) of basalts sampled from the base and top of the CLF (Sinton et al., 1998). However, the IN-SIMS age of the CLF does agree within error to an Albian ammonite found within a pelagic interval of the CLF (Fig. 8; Wiedman, 1978), which would indicate that the Turonian-Coniacian $^{40}Ar/^{39}Ar$ ages obtained by Sinton et al. (1998) may not truly represent the age of the CLF.

BONAIRE

The bedrock geology of Bonaire has been defined as a continuous succession of volcaniclastic, sedimentary, and intrusive rocks known as the Late Cretaceous "Washikemba Formation" (Pipjers, 1933; Klaver, 1976; Beets et al., 1977, 1984; Thompson, 2002; Thompson et al., 2004; Wright and Wyld, 2004). The "Washikemba Formation" is unconformably overlain by Maastrichtian and younger strata (Fig. 11). Prior studies have utilized both petrological and geochemical analyses to demonstrate that the "Washikemba Formation" does not contain exposures of the CLIP, but records a succession of volcanic rocks with a magmatic arc signature (e.g. Klaver, 1976; Donnelly and Rogers, 1980; Beets et al., 1984; Thompson, 2002; Thompson et al., 2004). These rocks of Bonaire are viewed to be part of the southern edge of the Cretaceous "Great Arc of the Caribbean" (Beets et al., 1984; Thompson et al., 2004).

Recent mapping by Wright and Wyld (2010) indicates that the "Washikemba Formation" of northwest Bonaire cannot be considered part of a single stratigraphic succession, but actually consists of two separate units that are in fault contact (Fig. 11). Wright and Wyld (2010) therefore renamed these rocks as the Washikemba Group and the Matijs Group. The Matijs Group refers to the Salina Matijs assemblage of prior workers (Klaver, 1976; Beets et al., 1977; Thompson, 2002), and is dominated by sedimentary rocks. The Washikemba Group consists almost entirely of igneous rocks, and refers to the remainder of the "Washikemba Formation" as previously defined in northwest Bonaire. The following summary of geologic relations on Bonaire is taken from Wright and Wyld (2010), except where noted otherwise.

Washikemba Group (WG)

The WG comprises the Wecua, Slagbaai and Branderis assemblages of prior workers (Klaver, 1976; Thompson, 2002) and consists mostly of felsic volcanics and shallow-level

intermediate and felsic intrusions (Fig. 11; Klaver, 1976; Thompson, 2002; Wright and Wyld, 2010). Two different suites of hypabyssal rocks intrude the WG. The lower part of the WG are intruded by diorite dikes and small sills, while the upper part are intruded by rhyodacite sills. At the top of the WG, Wright and Wyld (2010) located a distinctive conglomerate unit that was derived entirely from the underlying WG.

The age of the WG is constrained by the presence of mid to Late Albian ammonites from the lower part of the WG (Beets et al., 1977) and $^{40}Ar/^{39}Ar$ ages of 95 ± 2 Ma (Thompson, 2002) and 96 ± 4 Ma (Thompson et al., 2004) from the upper part of the WG. Wright and Wyld (2010) recently obtained similar U-Pb zircon ages of 98.2 ± 0.6 Ma and 94.6 ± 1.4 Ma from the upper part of the WG. Available data thus indicates that the WG accumulated over the interval from Albian to Cenomanian.

Matijs Group (MG)

The MG is divided into three separate sedimentary units: an argillite unit that is locally cross-cut by diabase stocks, a conglomerate unit, and a chert unit (Fig. 11).

The Matjis argillite occurs at the base of the unit and consists of pelagic and hemipelagic strata. The argillite unit is intruded by mafic stocks that are found only in the argillite unit (Fig. 11), and exhibit arc related trace element characteristics. The diabasic intrusions found in the MG are different than those in the WG due to the diabase being much less weathered, coarser grained, non-vesicular, and forming discrete bodies that have narrow contact metamorphic aureoles (Klaver, 1976; Thompson, 2002). The overlying conglomerate, referred to by prior workers as 'boulder beds' (Klaver, 1976; Thompson, 2002), consists of a distinctive polymictic conglomerate and breccia beds. The conglomerate unit contains paleontological evidence that

indicates a Coniacian age (Beets et al., 1977). The chert unit consists of pelagic strata that include thinly bedded chert, radiolarian chert, and argillaceous chert.

IN-SIMS Results from the Matijs diabase of Bonaire

Samples were collected from a diabase intrusion within the argillite unit of the Matijs Group (see figure 11 for sample location). The mineralogy of the diabase consists of plagioclase + epidote + clinopyroxene + opaques (Figs. 12A & 12B). Ages of seven baddeleyite analyses yielded a mean age of 111.6 ± 5.1 Ma (95% Conf.) (Fig. 13A).   Five zircon analyses yielded a mean age of 93 ± 10 Ma (95% Conf.) (Fig. 13B). A mean age of both the baddeleyite and zircon analyses resulted in an age of 102 ± 7.7 Ma (95% Conf.).   An age of 111.6 ± 5.1 Ma from seven baddeleyite analyses is considered to be representative of the age of the Matijs diabase because the zircon analyses resulted in discordant ages (Fig. 13B).

Implications for IN-SIMS Results from the Matijs diabase of Bonaire

IN-SIMS geochronological results from the diabase unit within the MG yielded an age of 111.6 ± 5.1 Ma from seven baddeleyite analyses. This IN-SIMS age in combination with Cenomanian U-Pb SHRIMP ages (98.2 ± 0.6 Ma and 94.6 ± 1.4 Ma; Wright and Wyld, 2010) from the WG indicates an overall span of arc activity that occurred on Bonaire from the Albian to Cenomanian (ca. 112-95 Ma). The 111.6 ± 5.1 Ma age of the Matijs diabase also provides geochronological data to support mapping evidence of Wright and Wyld (2010) that a fault separates the MG and WG. This fault relationship is clearly evident based upon the overlying MG (Albian) is older in age than the underlying WG (Cenomanian) (Fig. 11).

GRAN ROQUE

Gran Roque is located within the Los Roques Archipelago and is the only island that contains exposures of igneous and metamorphic basement beneath Neogene cover. The

basement of Gran Roque consists of a mafic complex of amphibolites intruded by altered gabbro. The mafic complex is intruded by tonalitic and quartz-dioritic intrusions with an age of 65.6 ± 1.4 Ma (U-Pb Zircon; Wright and Wyld, 2004), that occur as small bodies and dikes. All of these units are then intruded by numerous aplite and pegmatite dikes, with no available age information (Fig. 14; Aguerrevere and Lopez, 1938; Rost, 1938; Schubert and Moticska, 1972, 1973; Wright and Wyld, 2004)

Mafic Complex (Amphibolites + Gabbro)

The mafic complex of Gran Roque consists of amphibolites and altered cross-cutting, coarse-grained gabbro (Fig. 14; Aguerrevere and Lopez, 1938; Schubert and Moticska, 1972, 1973). Mineralogically the amphibolites consist of hornblende + plagioclase + epidote ± quartz ± opaques and the gabbro consists of plagioclase + clinopyroxene + actinolite. Early geochemical analysis of both the amphibolites and gabbro indicate a tholeiitic affinity in which the rocks may have formed in either a MORB or island arc setting (Santamaria and Schubert, 1974; Ostos, 1990; Ostos and Sisson, 2005). However, further geochemical analysis by Giunta et al. (2002) indicates that the amphibolites and gabbros have an oceanic plateau affinity. New geochemical data from this study is consistent with Giunta et al.'s (2002) hypothesis that the mafic complex of Gran Roque is representative of an oceanic plateau and new data from this study indicate that both the amphibolites and gabbros of Gran Roque lack a subduction related trace-element signature, have flat chondrite normalized REE patterns, and correlate well with geochemical data of known CLIP rocks of Aruba and Curaçao (Figs. 15A & 15B). This new geochemical data suggests a CLIP origin for the mafic complex of Gran Roque. The rocks of the mafic complex locally display spheroidal weathering features in which the weathering rinds are replaced by phosphate minerals (Marcano, 1873; Aguerrevere and Lopez, 1938; Rost, 1938).

Wright and Wyld (2004) postulate that the origin of these phosphate minerals is due to the reaction of guano from Cretaceous sea birds with the mafic complex. There is no evidence of spheroidal weathering on any of the younger arc intrusions and in places these arc rocks actually intrude into the phosphatized mafic complex.

The only direct age information available for the mafic complex are two K-Ar ages of 127 ± 15 Ma and 130 ± 14 Ma from hornblende separates of the amphibolites (Santamaria and Schubert, 1974). However, the age of the cross-cutting 65.6 ± 1.4 Ma quartz-diorite provides an upper age limit for the mafic complex of Gran Roque (Wright and Wyld, 2004).

IN-SIMS Results from the Gabbro of the Mafic Complex of Gran Roque

Samples were collected from the gabbro unit within the mafic complex (see figure 14 for sample location). The mineralogy of the gabbro unit consists of plagioclase + actinolite + clinopyroxene + opaques (Figs. 16A & 16B). Ages of 15 zircon analyses yielded a mean age of 87.0 ± 4.1 Ma (95% Conf.) (Fig. 17).

Implications for IN-SIMS Results from the Gabbro of the Mafic Complex of Gran Roque

An IN-SIMS age of 87.0 ± 4.1 Ma was determined for the cross-cutting gabbro of the mafic complex of Gran Roque from 15 zircon analyses. This Coniacian age provides an upper limit for the age of the mafic complex of Gran Roque.

SUMMARY OF NEW IN-SIMS DATA OF THE LEEWARD ANTILLES

IN-SIMS age results from this study of CLIP exposures from Aruba, Curaçao, and Gran Roque indicate a ~30 m.y. span of CLIP magmatism that occurred within the Leeward Antilles from the Aptian to Coniacian (ca. 115-87 Ma). An IN-SIMS age of 99.4 ± 4.5 Ma was determined for the diabase unit of the ALF from both nine baddeleyite and six zircon analyses. This age for the diabase unit of the ALF is slightly older than a Turonian fossil found within the

lower ALF (Fig. 5; MacDonald, 1968) and indicates that the ALF is at least Cenomanian in age. IN-SIMS analyses of diabase within the CLF yielded an age of 114.7 ± 7.4 Ma from eight baddeleyite analyses. This Aptian age is significantly older than previously reported Turonian $^{40}Ar/^{39}Ar$ ages (ca. 89-90 Ma) of basalts sampled from the base and top of the CLF (Sinton et al., 1998). However, the IN-SIMS age of the CLF does agree within error to an Albian ammonite found within a pelagic interval of the CLF (Fig. 8; Wiedman, 1978), which would indicate that the Turonian $^{40}Ar/^{39}Ar$ ages obtained by Sinton et al. (1998) may not truly represent the age of the CLF. An IN-SIMS age of 87.0 ± 4.1 Ma was determined for the cross-cutting gabbro of the mafic complex of Gran Roque from 15 zircon analyses. This Coniacian age provides an upper limit for the age of the mafic complex of Gran Roque.

　　IN-SIMS geochronological results from the diabase unit within the MG yielded an age of 111.6 ± 5.1 Ma from seven baddeleyite analyses. This IN-SIMS age in combination with Cenomanian U-Pb SHRIMP ages (98.2 ± 0.6 Ma and 94.6 ± 1.4 Ma; Wright and Wyld, 2010) from the WG indicates an overall span of arc activity that occurred on Bonaire from the Albian to Cenomanian (ca. 112-95 Ma). The 111.6 ± 5.1 Ma age of the Matijs diabase also provides geochronological data to support mapping evidence of Wright and Wyld (2010) that a fault separates the MG and WG (Fig. 11).
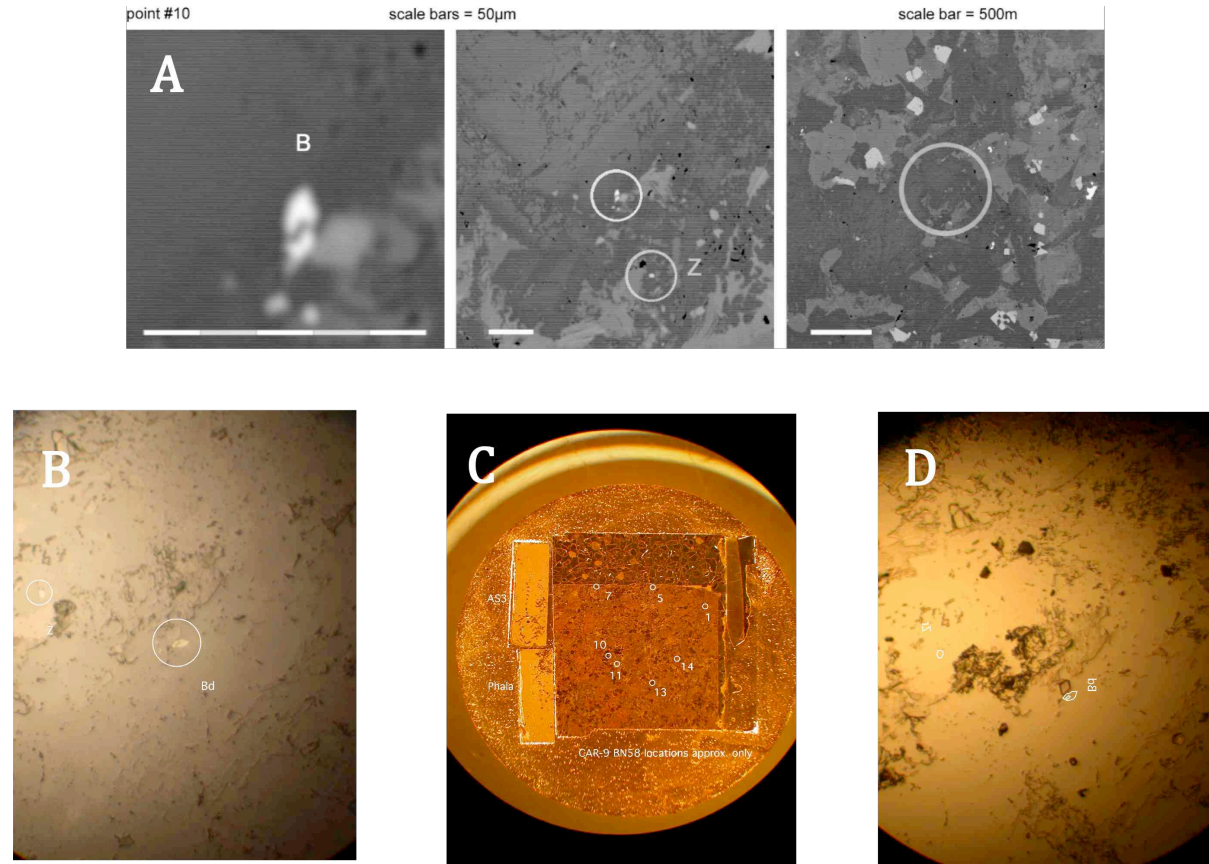
Figure 4: Photos of sample preparation for IN-SIMS analyses. (A) BSE images of potential targets (40x, 300x, 2000x). (B) Reflected light image of potential targets (40x objective). (C) Reflected light image of gold- coated target sections that are mounted on an epoxy disk along with baddeleyite and zircon standards (4x objective). (D) Reflected light image of gold-coated potential targets (40x objective).
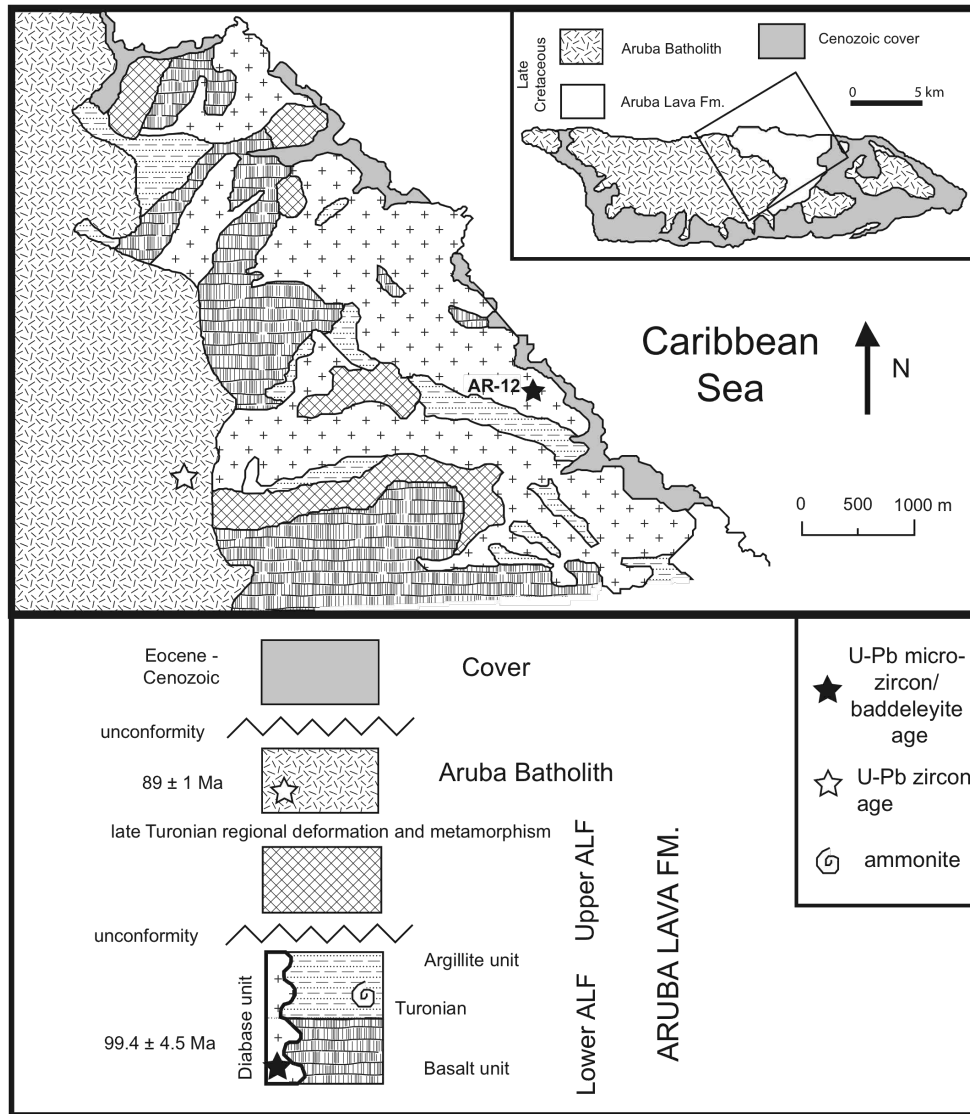
Figure 5: Geology of the island of Aruba. Inset shows a simplified map of the island (from Beets et al., 1996). Detailed geologic map of the central part of the island (see location in inset) and a generalized time-stratigraphic column from the Cretaceous to Eocene (modified from Wright and Wyld, 2010). The location of geochronological samples from this study are shown.
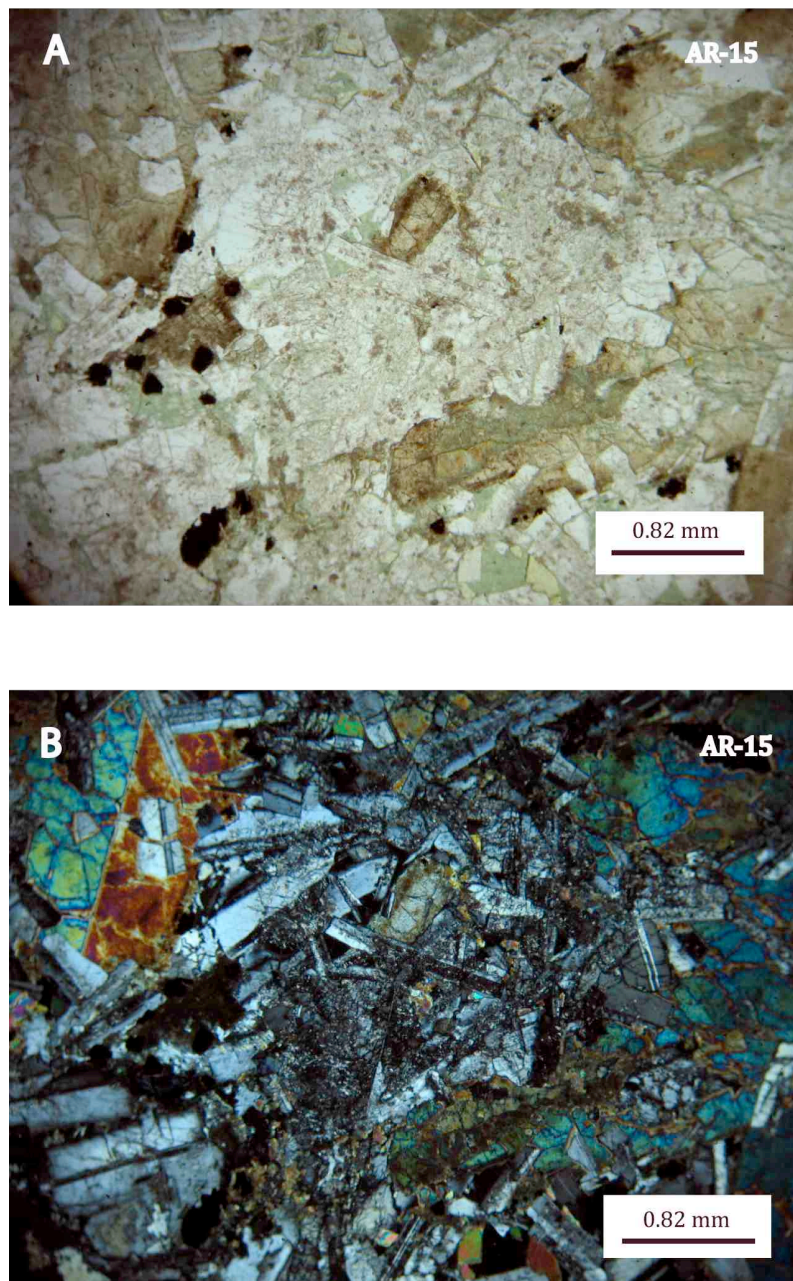
Figure 6: Photomicrographs of the diabase unit of the ALF (4x objective). (A) Plane polarized

light. (B) Cross polarized light.
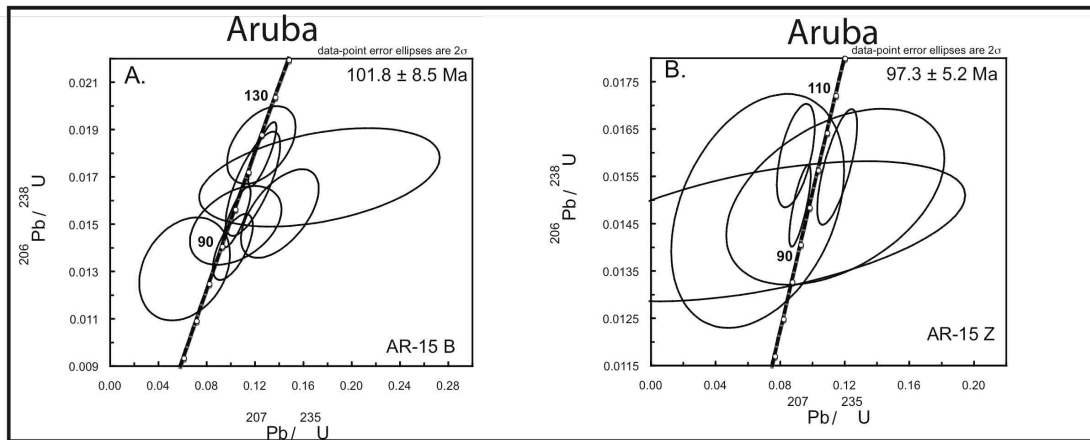
Figure 7: Concordia plots for IN-SIMS analyses of the diabase unit within the lower ALF. See figure 5 for sample location. (A) Nine baddeleyite analyses. (B) Six zircon analyses.
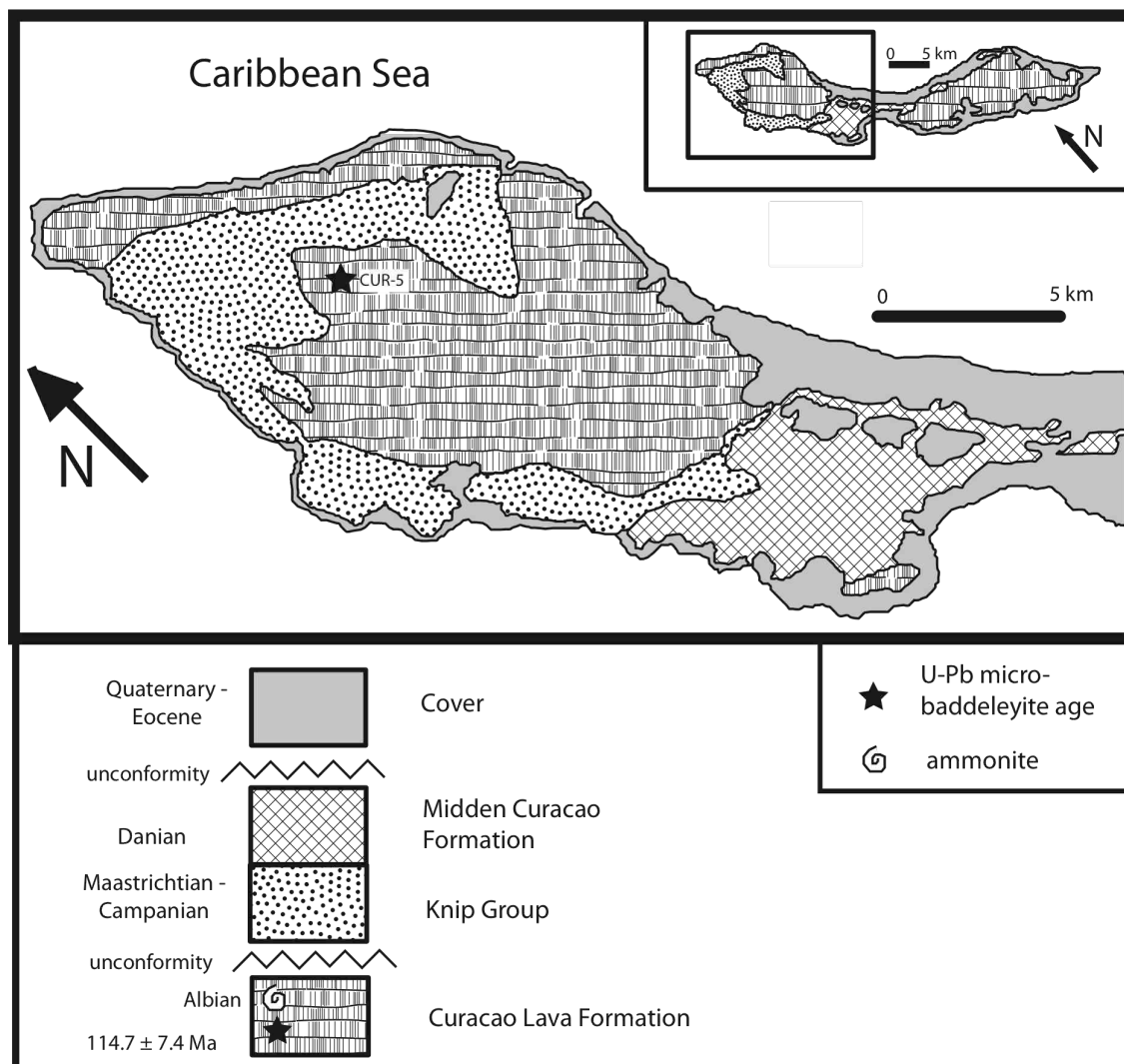
Figure 8: Geology of the island of Curaçao. Inset shows a simplified map of the island (from Beets, 1972). Detailed geologic map of the northwest part of the island (see location in inset) and a generalized time-stratigraphic column of Curaçao geology from the Cretaceous to Eocene (modified from Wright and Wyld, 2010). The location of geochronological samples from this study are shown.
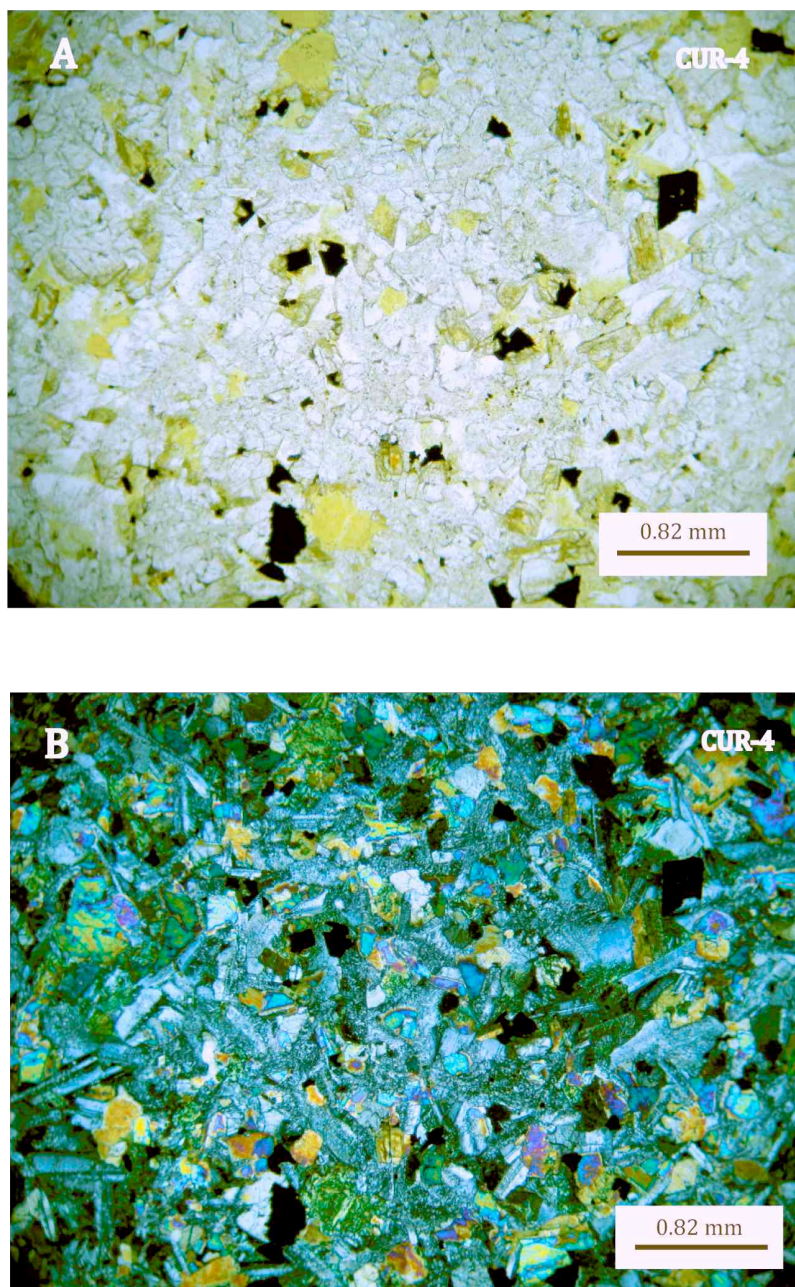
Figure 9: Photomicrographs of diabase from the CLF (4x objective). (A) Plane polarized light. (B) Cross polarized light.
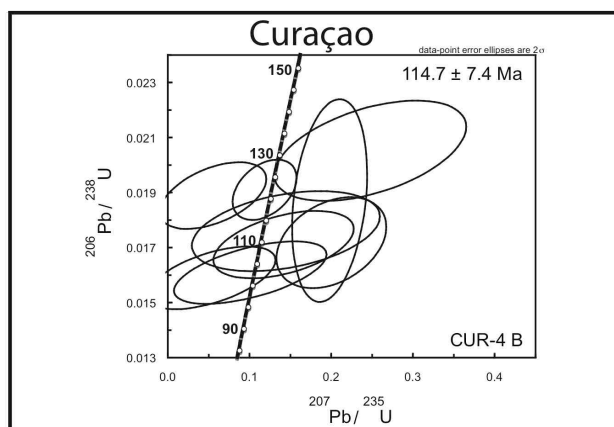
Figure 10: Concordia plot of IN-SIMS analyses of eight baddeleyite and one zircon from diabase within the CLF. See figure 8 for sample location.
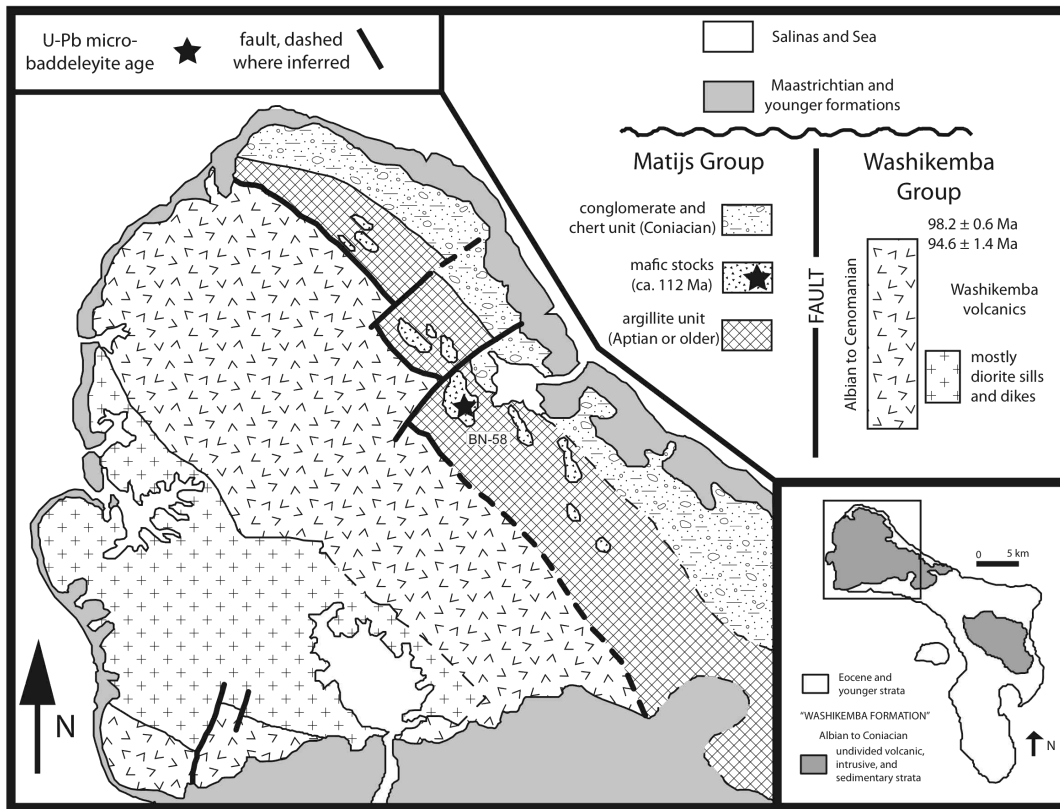
Figure 11: Geology of the island of Bonaire. Inset shows a simplified map of the island (from Klaver, 1976 and Thompson, 2002). Detailed geologic map of northwest Bonaire based on new mapping from Wright and Wyld (2010) and previous mapping by Beets (1972), Beets et al. (1977), and Klaver (1976), which shows the fault contact between the Washikemba Group and Matijs Group. The location of geochronological samples from this study are shown. A revised generalized time-stratigraphic column of Bonaire geology from the Cretaceous to Eocene is also shown (modified from Wright and Wyld, 2010).
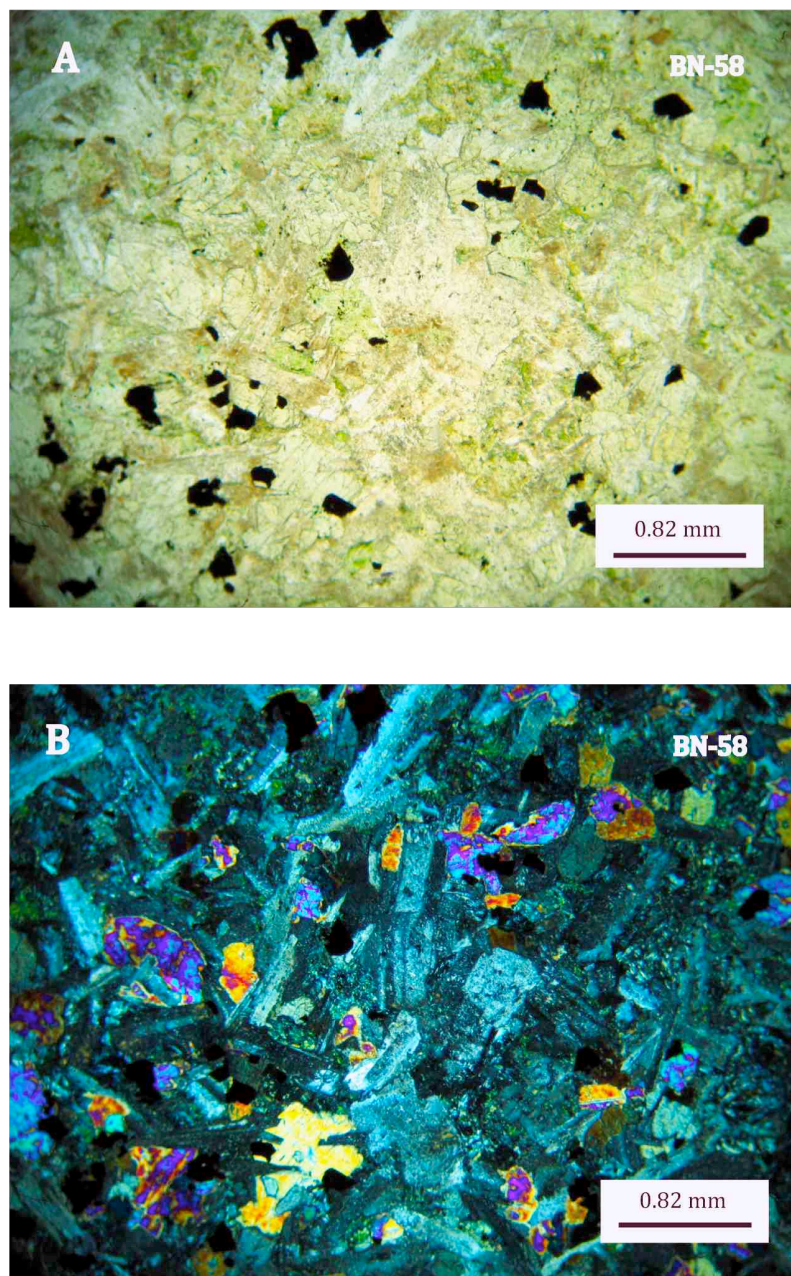
Figure 12: Photomicrographs of the diabase within the argillite unit of the Matijs Group (4x objective). (A) Plane polarized light. (B) Cross polarized light.
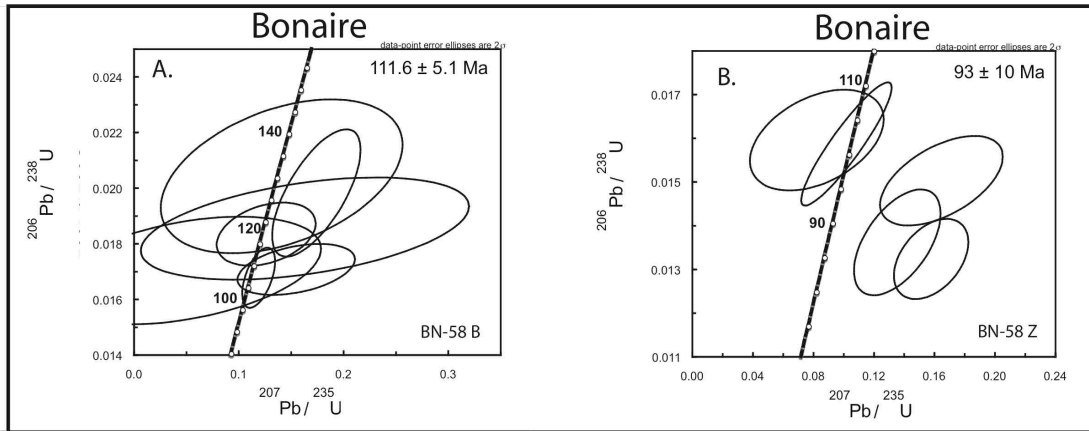
Figure 13: Concordia plots for IN-SIMS analyses of diabase within the argillite unit of the Matijs Group. See figure 11 for location. (A) Seven baddeleyite analyses. (B) Five zircon analyses.
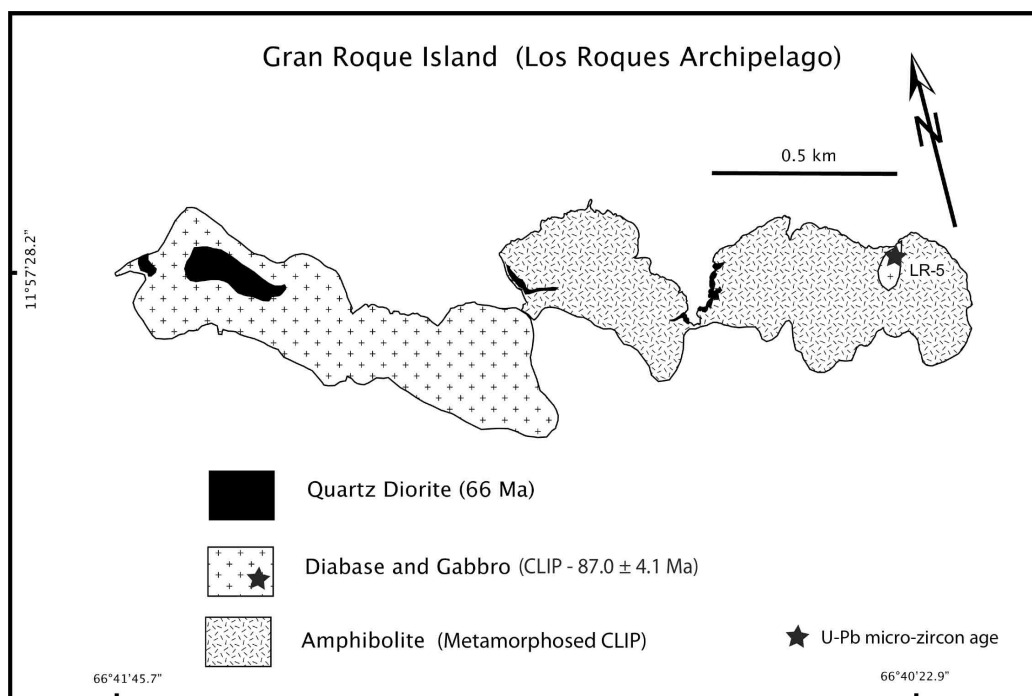
Figure 14: A simplified map of the island of Gran Roque, located in the Los Roques Archipelago (modified from Wright and Wyld, 2004). The location of geochronological samples from this study are shown.
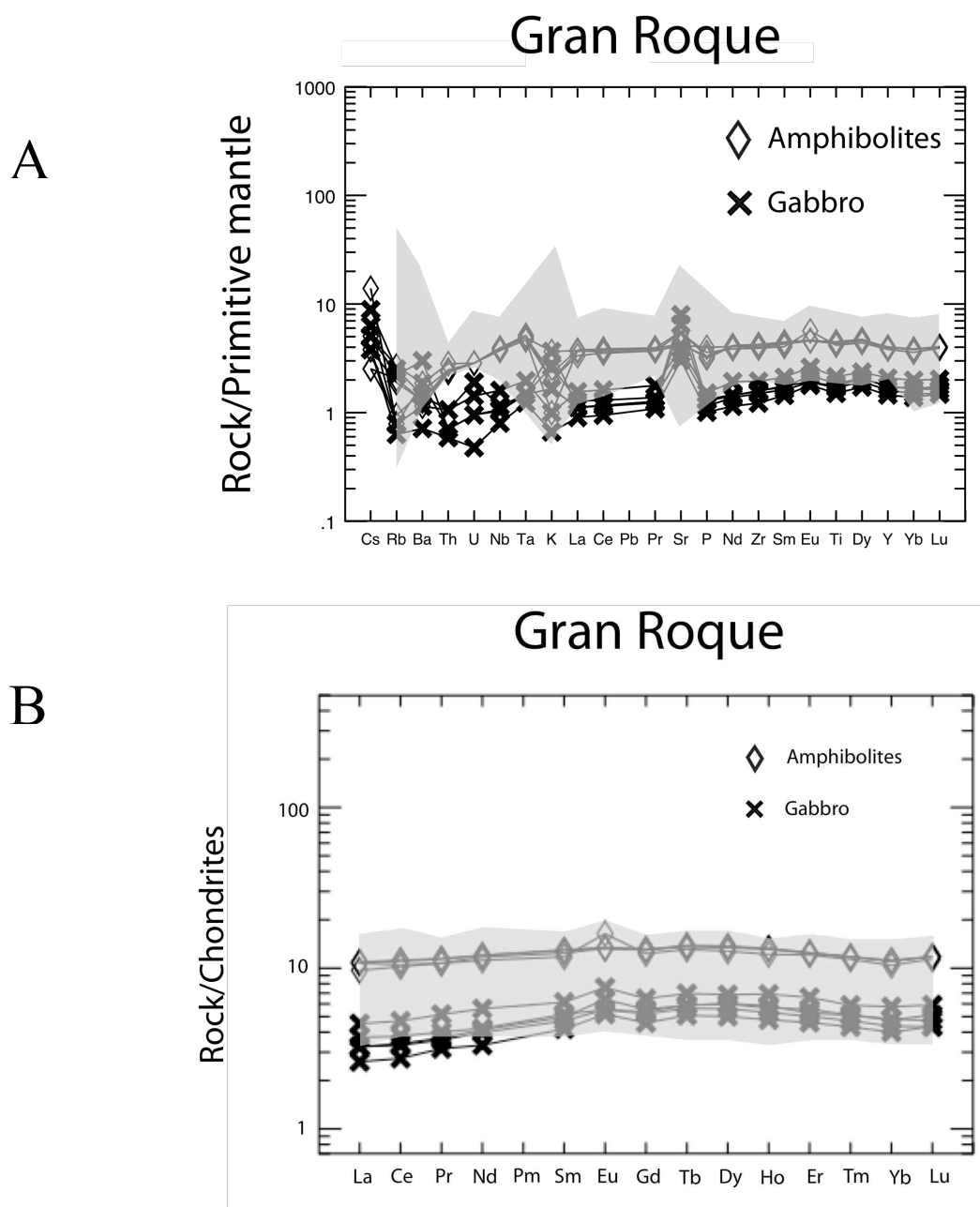
Figure 15: Geochemical plots comparing the amphibolites and gabbro (mafic complex) of Gran Roque to the geochemical range of the ALF and CLF. In all figures, the "diamond shape" represents the amphibolites of Gran Roque, the "X shape" represents the gabbros of Gran Roque, and the grey shading represents the range of geochemical data from the ALF

and CLF. (A) Multi-element plot normalized to primitive mantle (Sun and McDonough,

1989). (B) Chondrite-normalized REE diagram (Sun and McDonough, 1989).
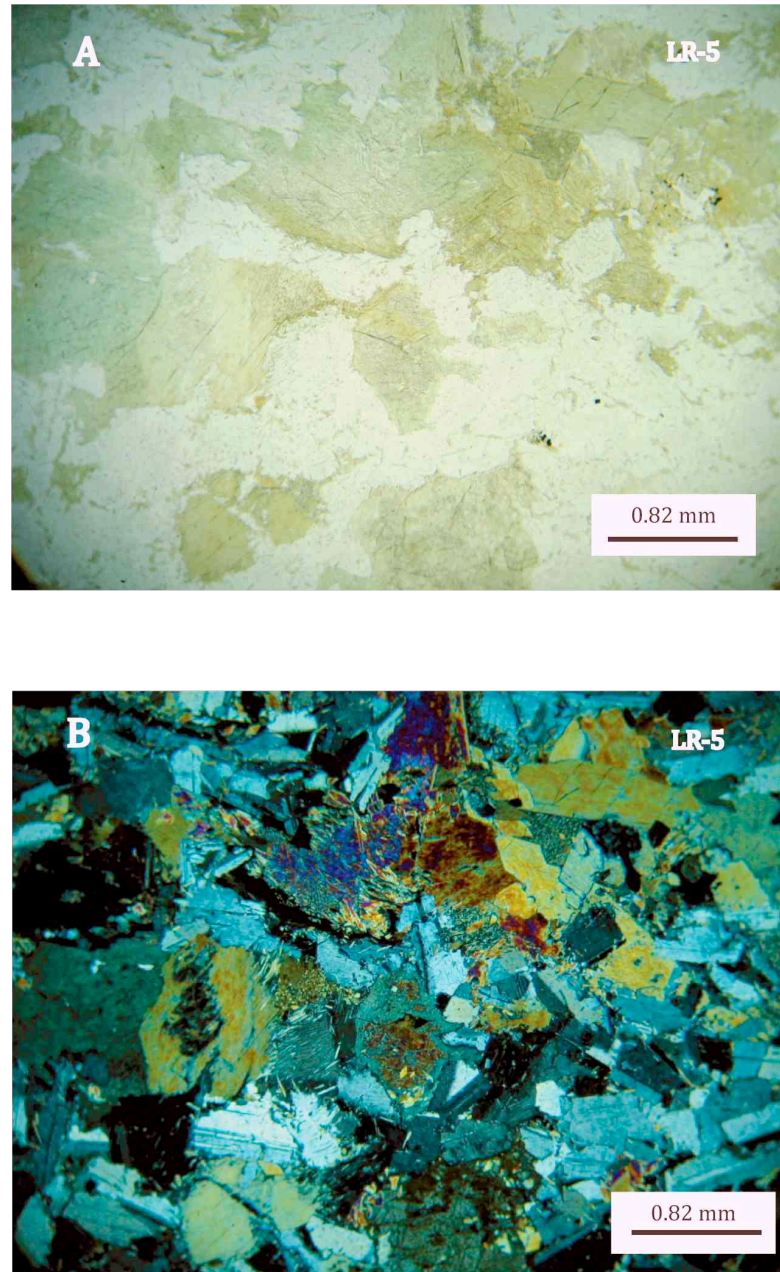
Figure 16: Photomicrographs of the gabbro unit of the mafic complex of Gran Roque (4x

objective). (A) Plane polarized light. (B) Cross polarized light.
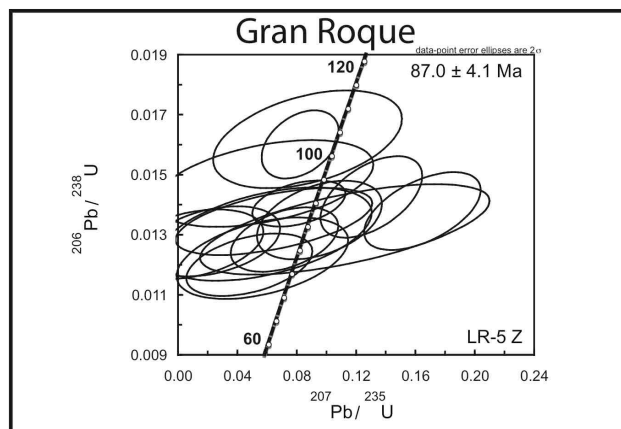
Figure 17: Concordia plot of IN-SIMS analyses of 15 zircon from the gabbro unit of the mafic complex of Gran Roque. See figure 14 for sample location.

CHAPTER 4

IMPLICATIONS FOR THE TEMPORAL EVOLUTION OF THE CLIP

The extensive duration of CLIP magmatism (~ 30 m.y.) within the Leeward Antilles islands of Aruba, Curaçao, and Gran Roque suggests that the simple plume head model for the formation of the CLIP within a short period of time (ca. 92-88 Ma) must be reevaluated (e.g. Sinton et al., 1998; Kerr et al., 2003). To explain the protracted history of the CLIP, two different models are presented: the Leeward Antilles islands of Aruba, Curaçao, and Gran Roque may be representative of (1) multiple pulses of oceanic plateau magmatism or (2) a continuous period of magmatism that lasted from the Aptian to Coniacian.

Due to the modality of ages presented with IN-SIMS analyses, the Leeward Antilles islands of Aruba, Curaçao, and Gran Roque could represent multiple pulses of oceanic plateau magmatism (Fig. 18). This age distribution can be accomplished by one hot spot with multiple pulses (Mauffret and Leroy, 1997) or by multiple hotspots derived from a similar source (Hauff et al., 2000). The similarity of IN-SIMS ages within error from Gran Roque and Aruba (Fig. 18), in conjunction with a Turonian fossil found intercalated in the ALF (Fig. 5) could indicate that these two exposures of the CLIP formed during the same pulse of plateau magmatism. However, CLIP exposures from Aruba and Cruacao could have also formed through entirely separate events. An IN-SIMS age of 114.7 ± 7.4 Ma from the CLF is significantly older and does not overlap with IN-SIMS ages from either Aruba or Gran Roque (Fig. 18). An Albian fossil found intercalated within the CLF (Fig. 8) also supports the IN-SIMS age of the CLF. This would suggest that the CLF may have formed by an entirely separate pulse of plateau magmatism that

was significantly older than the earlier pulse or pulses that created the CLIP exposures on Aruba and Gran Roque.

Another possible explanation for the IN-SIMS age distribution is that the CLIP exposures of the Leeward Antilles represent a continuous period of CLIP magmatism that occurred from the Aptian to Coniacian (ca. 115-87 Ma). However, if the CLIP was formed through an extended period of magmatism, the CLIP could not be considered a LIP (Coffin and Eldholm, 1994) and previous interpretations for the rate of emplacement of the CLIP would be drastically reduced.
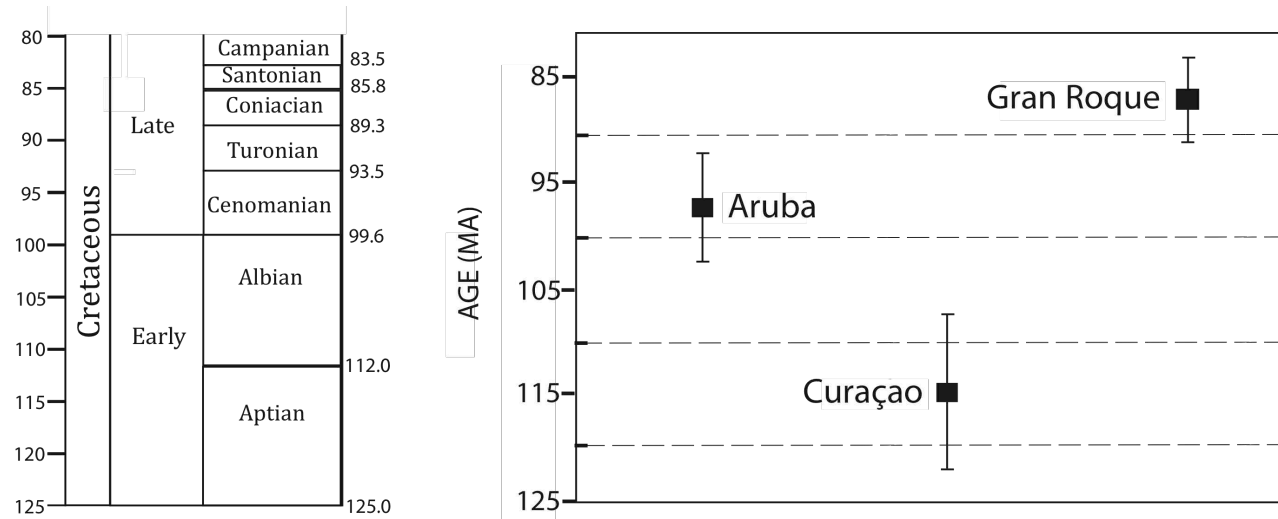
Figure. 18: An X-Y plot that graphically shows the IN-SIMS ages, with error bars, of CLIP exposures from Aruba, Curaçao, and Gran Roque. Geologic time scale from Gradstein et al., 2004

CHAPTER 5

FURTHER RESEARCH WITH THE IN-SIMS TECHNIQUE

The IN-SIMS U-Pb geochronological technique effectively obtained precise age data from mafic exposures of both oceanic plateau and arc magmatic rocks of the Caribbean. Due to the fact that IN-SIMS age determinations were conducted only within the Leeward Antilles islands of Aruba, Curaçao, Bonaire, and Gran Roque, definitive conclusions for the overall timing and duration of the CLIP and early arc magmatism cannot be made. However, important contributions are presented to guide further research projects that involve the CLIP and early arc magmatism.

Based upon the extended age range of IN-SIMS data, the hypothesis that the CLIP formed over a short period of time through a single pulse of magmatism (e.g. Sinton et al., 1998; Kerr et al., 2003) should be reevaluated. This hypothesis was mainly based upon $^{40}Ar/^{39}Ar$ radiometric ages from previous studies of the CLIP (Fig. 3). However, as observed through this study, there were significant differences between radiometric ages obtained with the $^{40}Ar/^{39}Ar$ method versus the IN-SIMS technique (Fig. 3). The validity of the IN-SIMS ages were upheld because the IN-SIMS ages also correlate with paleontological evidence found on Leeward Antilles islands (Table 1). The discrepancy between $^{40}Ar/^{39}Ar$ and IN-SIMS ages would imply that other $^{40}Ar/^{39}Ar$ ages of the CLIP could also be incorrect. To correct for these discrepancies, CLIP samples dated previously by the $^{40}Ar/^{39}Ar$ method should be dated again with the IN-SIMS technique to provide more precise and accurate ages. Reevaluation of these samples with the IN-SIMS method may present different ages than previous $^{40}Ar/^{39}Ar$ studies that could change

interpretations for the temporal evolution of the CLIP. In addition to the reevaluation of $^{40}Ar/^{39}Ar$ studies of the CLIP, more samples from ocean drilling, dredging, and on-land exposures of the CLIP also need to be collected and dated with the IN-SIMS technique to provide a more robust data set for conclusions on the timing and duration of CLIP magmatism to be determined.

Use of the IN-SIMS technique would provide improved resolution compared to traditional dating methods because oceanic plateau samples may be altered or have low potassium contents. The increase in accuracy of the IN-SIMS technique is important because this would provide a more reliable geochronological method to determine the temporal evolution of other oceanic plateaus throughout the world. This information could then be used to determine trends in oceanic plateau magmatism, such as their timing and duration.

Based upon the protracted history of IN-SIMS ages from CLIP exposures of the Leeward Antilles (Fig. 18), this could imply that other oceanic plateaus may form in a similar manner. This would suggest that oceanic plateaus may not form by a single, short-lived pulse of magmatism, but would occur over much longer periods of time than previously believed. The IN-SIMS technique can now provide valuable insight into the true formational history of oceanic plateaus from around the world.

REFERENCES

Aguerrevere, S.E., and Lopez, V.M., 1938, The geology of the island Gran Roque (Federal Dependencias) and its phosphate deposits: Venezuela, Bol. Geol. y Min., v. 2, no. 2-3-4, p. 155-181.

Alvarado, G.E., Denyer, P., and Sinton, C.W., 1997, The 89 Ma Tortugal komaatitic suite, Costa Rica: implications for a common geological origin of the Caribbean and eastern Pacific region from a mantle plume: Geology, v. 25, p. 439-442.

Aspden, J.A., 1984, The geology of the Western Cordillera, Department of Valle, Colombia (sheets 261, 278, 280, and 299): INGEOMINAS-Mission Britanica, Cali, Colombia.

Barrero, D., 1979, Geology of the Central Western Cordillera, west of Buga and Roldanillo, Colombia: Publicaciones Geologicas Especials del INGEOMINAS, v. 4, p. 1-75.

Baumgartner, P.O., 1984, El complejo ofiolitico de Nicoya (Costa Rica): Modelos estructurales analizados en funcion de las edades de los Radiolarios (Calloviense a Santoniense), in Spechmann, P., ed., Manual de Geologia de Costa Rica: Editorial Universidad de Costa Rica, San Jose-Costa Rica, p. 115-123.

Beardsley, A.G., and Ave Lallemant, H.G., 2007, Oblique collision and accretion of the Netherlands Leeward Antilles to South America: Tectonics, v. 26, p. 1-16.

Beets, D.J., 1972, Lithology and stratigraphy of the Cretaceous and Danian succession of Curacao [Ph.D. thesis]: Publication of Natuurwet, Studiekring Sur and Netherlands Antilles, no. 70, 153 p.

Beets, D.J., 1977, Cretaceous and Early Tertiary of Curacao, in 8th Caribbean Geological Conference Guide to Field Excursions: GUA Papers of Geology, Amsterdam, no. 10, p. 18-28.

Beets, D.J., Klaver, G.Th., Beunk, F.F., Kieft, G., and Maaskant, P., 1982, Picrities as parental magma of MORB-type tholeiites: Nature, v. 296, p. 341-343.

Beets, D.J., and MacGillavry, H.J., 1977, Outline of the Cretaceous and Early Tertiary history of Curaçao, Bonaire and Aruba: Guide to the field excursions on Curaçao, Bonaire and Aruba, GUA Papers of Geology v. 10 p. 1-6.

Beets, D.J., Maresch, W.V., Klaver, G. Th., 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., Shagam, R., eds., The Caribbean-South American Plate Boundary and Regional Tectonics: Geological Society of America Memoir, v. 162, p. 95-130.

Beets, D.J., Westerman, J.H., De Buisonje, P.H., Monen, H.P., Stienstra, P., Klaver, G.T., Ruiz, A.V., Curet, E.A., White, R.V., and Fouke, B.W., 1996, Geologic Map of Aruba: Publications Foundation for Scientific Research in the Caribbean Region, v. 140.

Bence, A.E., Papike, J.J., and Ayuso, R.A., 1975, Petrology of submarine basalts from the Central Caribbean: DSDP Leg 15: Journal of Geophysical Research, v. 80, p. 4775-4805.

Bittenbender, P.E., Bean, K.W., and Gensler, E.G., 2003, Minreal Investigations in the Delta River Mining District, east-central Alaska 2001-2002: U.S. Bureau of Land Management- Alaska, Open-File Report 91, 88 p.

Boland, M.P., McCourt, W.J., and Beate, B., 2000, Mapa geologico de la Cordillera Occidental del Ecuador entre 0˚-1˚N, escala 1/200000: Ministerio de Energia y Minas-BGS publs, Quito.

Bourgois, J., Toussaint, J.F., Gonzales, H., Axema, J., Calle, B., Desmet, A., Murcia, L.S., Acevedo, A.P., Parra, E., and Tournon, J., 1987, Geological history of the Cretaceous ophiolitic complexes of NW South America (Colombian Andes): Tectonophysics, v. 143, p. 307-327.

Bouysse, P., 1988, Opening of the Grenada back-arc Basin and evolution of the Caribbean plate during the Mesozoic and early Paleogene: Tetonophysics, v. 149, p. 121-143.

Bristow, C.R., and Hoffstetter, R., 1977, Ecuador. Lexique Stratigraphique International, V. CNRS, Pars, 5a2.

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

Campbell, S.W., 1981, Geology and genesis of copper deposits and associated host rocks near the Quill Creek area, southwestern Yukon: Ph. D. thesis, Vancouver, University of British Columbia, 215 p.

Campbell, I.H., 2007, Testing the plume theory: Chemical Geology, v. 241, p. 153-176.

Campbell, I.H., and Griffiths, R.W., 1990, Implications of mantle plume structure for the evolution of flood basalts: Earth and Planetary Science Letters, v. 99, p. 79-93.

Case, J.E., Duran, S.L., Lopez, A., and Moore, W.R., 1971, Tectonic investigations on western Colombia and eastern Panama: Geological Society of America Bulletin, v. 82, p. 2685-2712.

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

Castillo, P., Pringle, M.s., and Carlson, R.W., 1994, East Mariana Basin tholeiites: Jurassic ocean crust or Cretaceous rift basalts related to the Ontong Java plume: Earth and Planetary Science Letters, v. 123, p. 139-154.

Chambers, L.M., Pringle, M.S., and Fitton, J.G, 2002, Age and duration of magmatism on the Ontong Java Plateau: ^{40}Ar-^{39}Ar results from ODP Leg 192, Abstract V71B-1271: Eos, Transactions of the Geophysical Union, v. 83, p. F47.

Coffin, M.F., and Eldholm, O., 1994, Large igneous provinces: crustal structure, dimensions, and external consequences: Reviews of Geophysics, v. 32, no. 1, p. 1-36.

Coffin, M.F., Pringle, M.S., Duncan, R.A., Gladczenko, T.P., Storey, M., Muller, R.D., and Gahagan, L.A., 2002, Kerguelen magma output since 130 Ma: Journal of Petrology, v. 43, p. 1121-1139.

Del Giudice, D., and Recchi, G., 1969, Geologia del area del projecto minero de Azuero Ejectora, Informe Technico preparado para el Gobierno de la Republica de Panama por las Naciones Unidas: Actuando y Participando como Agencia, p. 1-48.

Dengo, 1962, Tectonic-igneous sequence in Costa Rica, in Engel, A.E.J., James, H.J., and Leonard, B.F., eds., A volume to honor A.F. Budington: Geological Society of America, Special Volume, p. 133-161.

Deniaud, T., 2000, Enregistrement sedimentaire et structural de l'evolution geodynamique des Andes equatoriennes au cours du Neogene: etude des bassins d'avant-arc et bilans de masse: Geologie Alpine, Memoire, v. 32.

Denyer, P., and Baumgartner, P.O., 2006, Emplacement of Jurassic-Lower Cretaceous radiolarites of the Nicoya Complex (Costa Rica): Geologica Acta, v. 4, p. 203-218.

Denyer, P., Baumgartner, P.O., and Gazel, E., Characterization and tectonic implications of Mesozoic-Cenozoic oceanic assemblages of Costa Rica and Western Panama: Geologica Acta, v. 4, p. 219-235.

Denyer, P., and Gazel, E., 2009, The Costa Rican Jurassic to Miocene oceanic complexes: Origin, tectonics and relations: Journal of South America Earth Sciences, v. 28, p. 429-442.

Diebold, J.B., Stoffa, P.L., Buhl, P., and Truchan, M., 1981, Venezuelan basin crustal structure: Journal of Geophysical Research, v. 86, p. 7901-7923.

Donnelly, T.W., 1973, Late Cretaceous basalts from the Caribbean, a possible flood basalt province of vast size: EOS, v. 54, p. 401-414.

Donnelly, T.H., 1994, The Cretaceous basalt association: a vast igneous province that includes the Nicoya Complex of Costa Rica: Profil, v. 1, p. 17-45.

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 Geology of North America, vol. H, The Caribbean Region: Geological Survey of America, Boulder, Colorado, p. 339-374.

Donnelly, T.W., Melson, W., Kay, R., and Rogers, J.J.W., 1973, Basalts and dolerites of late Cretaceous age from the central Caribbean: Initial Reports of the Deep Sea Drilling Project, v. 15, p. 989-1004.

Donnelly, T.W., and Rogers, J.J.W., 1978, The distribution of igneous rock suites through the Caribbean: Geologie en Mijnbouw, v. 57, p. 151-162.

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

Draper, G., and Lewis, J.F., 1989, Petrology and structural development of the Duarte Complex, central Republica Dominicana: A preliminary account and some tectonic implications, in Duque Caro, H., ed., Transactions of the 10th Caribbean Geological Conference: INGEOMINAS, p. 103-112.

Draper, G., and Lewis, J.F., 1991, Metamorphic belts in central Espanola, in Mann, P., Draper, G., and Lewis, J., eds., Geologic and Tectonic Development of the North American- Caribbean Plate Boundary in Espanola: Special Paper Geological Society of America, v. 262, p. 29-46.

Driscoll, N.W., and Diebold, J.B., 1998, Deformation of the Caribbean region: One plate or two?: Geology, v. 26, p. 1043-1046 .

Duncan, R.A., 2002, A time frame for construction of the Kerguelen Plateau and Broken Ridge: Journal of Petrology, v. 43, p. 1109-1119.

Duncan, R.A., and Hargraves, R.B., 1984, Plate tectonic evolution of the Caribbean in the mantle reference frame, in Bonini, W.E., Hargraves, R.B., Shagam, R., eds., The Caribbean- South American Plate Boundary and Regional Tectonics: Geological Society of America Memoir, v. 162, p. 95-130.

Duncan, R.A., and Richards, M.A., 1991, Hotspots, mantle plumes, flood basalts, and true polar wander: Reviews of Geophysics, v. 29, p. 31-50.

Edgar, N.T., Ewing, J.I., and Hennion, J., 1971, Seismic refraction and reflection in the Caribbean Sea: AAPG Bulletin, v. 55, p. 833-870.

Edgar, N.T. and Saunders, J.B., 1973, Initial Reports of the Deep Sea Drilling Project: U.S. Government Printing Office, Washington, DC, v. 15, 1135 p.

Escuder-Viruete, J., Perez-Estaun, A., Contreras, F., Joubert, M., Weis, D., Ullrich, T.D., and Spadea, P., 2007, Plume mantle source heterogeneity through time: Insights from the Duarte Complex, Hispaniola, northern Caribbean: Journal of Geophysical Research, v. 112, p. 1-19.

Farnetani, C.G., Legras, B., and Tackley, P.J., 2002, Mixing and deformations in mantle plumes: Earth and Planetary Science Letters, v. 196, p. 1-15.

Farnetani, C.G., and Richards, M.A., 1995, Thermal entrainment and melting in mantle plumes: Earth and Planetary Science Letters, v. 136, p. 251-267.

Farnetani, C.G., and Samuel, H., 2005, Beyond the thermal plume paradigm: Geophysical Research Letters, v. 32.

Feininger, T., and Bristow, C.R., 1980, Cretaceous and Paleogene geologic history of Coastal Ecuador: Geologische Rundschau, v. 69, p. 849-874.

Fitton, F.G., and Godard, M., 2004, Origin and evolution of magmas on the OJP, in Fitton, J.G., Mahoney, J.J., Wallace, P.J., and Saunders, A.D., eds., Origin and Evolution of the OJP: Geological Society, London, Special Publications, v. 229, p. 151-178.

Fitton, J.G., Mahoney, J.J., Wallace, P.J., and Saunders, A.D., 2004, Origin and evolution of the Ontong Java Plateau: Introduction, in Fitton, J.G., Mahoney, J.J., Wallace, P.J., and Saunders, A.D., eds., Origin and Evolution of the Ontong Java Plateau: Geological Society, London, Special Publications, v. 229, p. 1-8.

Fox, P.J., Ruddiman, W.F., Ryan, W.B.F., and Bruce, C., 1970, The geology of the Caribbean Crust, I, Beata Ridge: Tectonophysics, vol. 10, p. 495-513.

Gansser, A., 1973, Facts and theories on the Andes: Journal of the Geological Society, London, v. 129, p. 93-131.

Giunta, G., Beccaluva, L., Coltorti, M., Siena, F., and Vaccaro, C., 2002, The southern margin of the Caribbean plate in Venezuela: tectono-magmatic setting of the ophiolite units and kinematic evolution: Lithos, v. 63, p. 19-40.

Gladczenko, T.P., Coffin, M.F., and Eldholm, O., 1997, Crustal structure of the Ontong Java Plateau: modeling of new gravity and existing seismic data: Journal of Geophysical Research, v. 102, p. 22711-22729.

Goosens, P.J., and Rose, W.I., 1973, Chemical composition and age determination of tholeiitic rocks in the Basic Igneous Complex, Ecuador: Geological Society of America Bulletin, v. 84, p. 1043-1052.

Goosens, P.J., Rose, W.I., and Flores, D., 1977, Geochemistry of tholeiites of the Basic Igneous Complex of northwestern South America: Geological Society of America Bulletin: v. 88, p. 1711-1720.

Gradstein, F.M., Ogg, J.G., Smith, A.G., Agterberg, F.P., Bleeker, W., Cooper, R.A., Davydov, V., Gibbard, P., and others, 2004, A Geologic Time Scale 2004: Cambridge University Press, ~500 p.

Greene, A.R., Scoates, J.S., Weis, D., Katvala, E.C., Israel, S., and Nixon, G.T., 2010, The architecture of oceanic plateaus revealed by the volcanic stratigraphy of the accreted Wrangellia oceanic plateau: Geosphere, v. 6, no. 1, p. 47-73.

Hastie A.R., and Kerr, A.C., 2010, Mantle plume or slab window? Physical and geochemical constraints on the origin of the Caribbean oceanic plateau: Earth-Science Reviews, v. 98, p. 283-293.

Hastie, A.R., Kerr, A.C., Mitchell, S.F., and Miller, I.L., 2008, Geochemistry and petrogenesis of Cretaceous oceanic plateau lavas in eastern Jamaica: Lithos, v. 101, p. 323-343.

Hauff, F., Hoernle, K., van der Bogaard, P., Alvarado, G., and Garbe-Schoenberg, D., 2000, Age and geochemistry of basaltic complexes in western Costa Rica: contributions to the geotectonic evolution of Central America: Geochemistry, Geophysics, Geosystems, v. 1, p. 1009.

Hauff, F., Hoernle, K., Schmincke, H.-U., and Werner, R., 1997, A mid Cretaceous origin for the Galapagos hotspot: volcanological, petrological and geochemical evidence from Costa Rican oceanic crustal fragments, Geologische Rundschau, v. 86, p. 141-155.

Hauff, F., Hoernle, K., Tilton, G., Graham, D.W., and Kerr, A.C., 2000, Large volume recycling of oceanic lithosphere over short time scales: Geochemical constraints from the Caribbean Large Igneous Province: Earth and Planetary Science Letters, v. 174, p. 247-263.

Helmers, H., and Beets, D.J., 1977, Geology of the Cretaceous of Aruba, Eighth Caribbean Geological Conference Guide to the Field Excursions on Curacao, Bonaire, and Aruba: GUA Paper of Geology, v. 10, p. 29-35.

Herzberg, C., and O'Hara, M.J., 2002, Plume-associated ultramafic magmas of Phanerozoic age: Journal of Petrology, v. 43, p. 1857-1883.

Hoernle, K. and Hauff, V., 2007, Oceanic igneous complexes, in Bundschuh, J., and Alvarado, G., eds., Geology of Central America: Leiden, the Netherlands, Taylor and Francis, p 523-547.

Hoernle, K., Hauff, F., and van den Bogaard, P., 2004, 70 m.y. history (139-69 Ma) for the Caribbean large igneous province: Geology, v. 32, p. 697-700.

Hoernle, K., van der Bogaard, P., Werner, R., Lissinna, B., Hauff, V., Allvarado, G., and Garbe-Schonberg, D., 2002, Missing history (16-71 Ma) of the Galapagos hotspot: Implications for the tectonic and biological evolution of the Americas: Geology, v. 30, p. 795-798.

Hughes, R.A., and Pilatasig, L.F., 2002, Cretaceous and Cenozoic terrane accretion in the Cordillera Occidental of the Andes of Ecuador: Tectonophysics, v. 345, p. 29-48.

Hughes, R.A., Bermudez, R., and Espinel, G., 1998, Mapa geologica de la Cordillera Ocidental del Ecuador entre 0-1 S, escala 1:2000000: CODIGEM-Ministerio de Energia y Minas-BGS publ, Quito, Nottingham.

Jackson. T.A., 1987, The petrology of Jamaican Cretaceous and Tertiary volcanic rocks and their tectonic significance, in Ahmad, R., ed., Proceedings of a Workshop on the Status of Jamaican Geology: Geological Society of Jamaica, Kingston, p. 107-119.

Jackson, T.A., and Robinson, E., 1994, The Netherlands and Venezuelan Antilles, in Donovan, S.K., and Jackson, T.A., eds., Caribbean Geology: An Introduction: University of the West Indies Public Association, p. 249-263.

Jackson, T.A., Rodrigues, K., and Smith, T.E., 1980, The composition and tectonic importance of Cretaceous pillow lavas from Whitehall, St. Thomas, Jamaica: Journal of the Geological Society of Jamaica, v. 19, p. 40-45.

Jaillard, E., Bengtson, P., Ordonez, M., Vaca, W., Dhondt, A., Suarez, J., and Toro, J., 2008, Sedimentary record of terminal Cretaceous accretions in Ecuador: the Yunguilla Group in the Cuenca area: Journal of South American Earth Sciences, v. 25, p. 133-144.

Jaillard, E., Lapierre, H., Ordonez, M., Toro Alava, J., Amortegui, A., and Vanmelle, J., 2009, Accreted oceanic terranes in Ecuador: southern edge of the Caribbean Plate?: in James, K.H., Lorente, M.A., and Pindell, J.L., eds., The Origin and Evolution of the Caribbean Plate: Geological Society, London, Special Publications, v. 328, p. 469-485.

Jaillard, E., Ordonez, M., Benitez, S., Berrones, G., Jimenez, N., Montenegro, G., and Zambrano, I., 1995, Basin development in an accretionary, oceanic-floored fore-arc setting: Southern coastal Ecuador during Late Cretaceous-late Eocene time, in Tankard, A.J., Suarez Soruco, R., and Welsink, H.J., eds., Petroleum Basins of South America: American Association of Petroleum Geologists Memoir, v. 62, p. 615-631.

Jaillard, E., Ordonez, M., Suarez, J., Toro, J., Iza, D., and Lugo, W., 2004, Stratigraphy of the Late Cretaceous-Paleogene deposits of the Western Cordillera of Central Ecuador: Geodynamic implications: Journal of South American Earth Sciences, v. 17, p. 49-58.

Jolly, W.T., Lidiak, E.G., and Dickin, A.P., 2006, Role of crustal melting in petrogenesis of the Cretaceous Water Island Formation (Virgin Islands), northeast Antilles island arc: Geologica Acta, v. 4, p. 7-33.

Kempton, P.D., Fitton, J.G., Saunders, A.D., Nowell, G.M., Taylor, R.N., Hardarson, B.S., and Pearson, G., 2000, The Iceland plume in space and time: a Sr-Nd-Pb-Hf study of the North Atlantic rifted margin: Earth and Planetary Science Letters, v. 177, p. 255-271.

Kerr, A.C., 1998, Oceanic plateau formation: a cause of mass extinction and black shale deposition around the Cenomanian-Turonian boundary: Journal of Geological Society, London, v. 155, p. 619-626.

Kerr, A.C., 2005, Oceanic LIPs: the kiss of death: Elements, v. 1, p. 289-292.

Kerr, A.C., Aspden, J.A., Tarney, J., and Pilatasig, L.F., 2002a, The nature and provenance of accreted oceanic blocks in western Ecuador: Geochemical and tectonic constraints: Journal of the Geological Society of London, v. 159, p. 577-594.

Kerr, A.C., Tarney, J., Kempton, P.D., Spadea, P., Nivia, A., Marriner, G.F., and Duncan, R.A., 2002b, Pervasive mantle plume head heterogeneity: Evidence from the late Cretaceous Caribbean-Colombian Oceanic Plateau: Journal of Geophysical Research, v. 107, no. 7, DOI 10.1019, 2001JB000790.

Kerr, A.C., Marriner, G.F., Tarney, J., Nivia, A., Saunders, A.D., Thirlwall, M.F., and Sinton, W., 1997, Cretaceous Basaltic Terranes in Western Colombia: Elemental, Chronological and Sr-Nd Isotopic Constrains on Petrogenesis: Journal of Petrology, v. 38, p. 677-702.

Kerr, A.C., Pearson, D.G., and Nowell, G.M., 2009, Magma source evolution beneath the Caribbean oceanic plateau: New insights from elemental and Sr-Nd-Pb-Hf isotopic studies of ODP Leg 165 Suite 1001 basalts, in James, K.H., Lorente, M.A., and Pindell, J.L., eds., Geology of Middle America and origin of the Caribbean Plate, Geological Society of London Special Publications 328, p. 809-827.

Kerr, A.C., Tarney, J., Marriner, G.F., Klaver, G.T., Saunders, A.D., and Thirlwall, M.F., 1996, 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., and Saudners, A.D., 1996, 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., Tarney, J., Marriner, G.F., Nivia, A., and Saunders, A.D., 1997, The Caribbean-Columbian Cretaceous igneous complex: The internal anatomy of an oceanic plateau, in Mahoney, J.J., and Coffin, M.F., eds., Large igneous provinces: Continental, oceanic, and planetary flood volcanism: American Geophysical Union Geophysical Monography 100, p. 123-144.

Kerr, A.C., Tarney, J., Marriner, G.F., Nivia, A., Saunders, A.D., and Klaver, G. Th., 1996, 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., White, R.V., and Saunders, A.D., 2000, LIP reading: Recognizing oceanic plateaux in the geological record: Journal of Petrology, v. 41, p. 1041-1056.

Kerr, A.C., White, R.V., Thompson, P.M.E., Tarney, J., and Saunders, A.D., 2003, No oceanic plateau – no Caribbean plate? The seminal role of an oceanic plateau in Caribbean plate evolution, in C. Bartolini, Buffler, R.T., and Blickwede, J., eds., The Circum-Gulf of Mexico and the Caribbean: Hydrocarbon habitats, basin formation, and plate tectonics, AAPG Memoir 79, p. 126-168.

Klaver, G.Th., 1976, The Washikemba Formation, Bonaire: MSc thesis, Utrect, Netherlands.

Klaver, G.Th., 1987, The Curacao lava formation: an ophiolitic analogue of the anomalous thick layer 2B of the mid-Cretaceous oceanic plateaus in the western Pacific and central Caribbean [Ph.D. dissertation]: University of Amsterdam, The Netherlands, GUA Papers of Geology, v. 27, 168p.

Krawinkel, H., Wozazek, S., Krawinkel, J., and Hellmann, W., 1999, Heavy-mineral analysis of and clinopyroxene geochemistry applied to provenance analysis of lithic sandstones from the Azuero-Sona Complex (NW Panama): Sedimentary Geology, v. 124, p. 149-168.

Kuijpers, E., 1980, The geologic history of the Nicoya Ophiolite Complex, Costa Rica, and its geotectonic significance: Tectonophysics, v. 68, p. 233-255.

Lapierre, H., Bosch, D., Dupuis, V., Polve, M., Maury, R., Hernandez, J., Monie, P., Yeghicheyan, D., Jaillard, E., Tardy, M., Mercier de Lepinay, B., Mamberti, M., Desmet, A., Keller, F., and Senebier, F., 2000, Multiple plume events in the genesis of the peri-Caribbean Cretaceous oceanic plateau province: Journal of Geophysical Research, v. 105, p. 8403-8421.

Lapierre, H., Depuis, V., de Lepinay, B.M., Bosch, D., Monie, P., Tardy, M., Maury, R.C., Hernandez, J., Polve, M., Yeghicheyan, D., and Cotton, J., 1999, Late Jurassic oceanic crust and Upper Cretaceous Caribbean plateau picritic basalts exposed in the Duarte igneous complex, Hispaniola: Journal of Geology, v. 107, p. 193-207.

Lapierre, H., Dupuis, V., de Lepinay, B.M., Tardy, M., Ruiz, J., Maury, R.C., Hernandez, J., and Loubet, M., 1997, Is the Lower Duarte Complex (Espanola) a remnant of the Caribbean plume generated oceanic plateau? : Journal of Geology, v. 105, p. 111-120.

Larson, R.L., 1991, Geological consequences of superplumes: Geology, v. 19, p. 547-550.

Larson, R.L., and Erba, E., 1999, Onset of the mid-Cretaceous greenhouse in the Barremian-Aptian: igneous events and the biological, sedimentary, and geochemical responses: Paleoceanography, v. 14, p. 663-678.

Lassiter, J.C., 1995, Geochemical investigations of plume-related lavas: Constraints on the structure of mantle plumes and the nature of plume/lithosphere interactions: Ph. D. thesis, Berkeley, University of California, 231 p.

Leckie, R.M., Bralower, T.J., and Cashman, R., 2002, Oceanic anoxic events and plankton evolution: biotic response to tectonic forcing during the mid-Cretaceous: Paleoceanography, v. 17, p. 1041.

Lewis, J.F., Draper, G., and Burgi, D., 1983, Geochemistry and petrology of high magnesian metabasalts of the Duarte Complex, Dominican Republic, in Duque Caro, H., ed., Transactions of the 10th Caribbean Geological Conference: INGEOMINAS, p. 47-48.

Lewis, J.F., Escuder-Viruete, J., Hernaiz Huerta, P.P., Gutierrez, G., Draper, G., and Perez Estuan, A., 2002, Subdivision geoquimica del Arco Isla Circum-Caribeno, Cordillera Central Dominicana: Implicaciones para la formacion, acrecion y crecimiento cortical en um ambiente intraoceanico: Acta Geologia Hispaniola, v. 37, p. 81-122.

Lewis, J.F., Hames, W.E., and Draper, G., 1999, Late Jurassic oceanic crust and Upper Cretaceous Caribbean Plateau picritic basalts exposed in the Duarte igneous complex, Espanola: A discussion: Journal of Geology, v. 107, p. 505-508.

Lewis, J.F., and Jimenez, J.G., 1991, Duarte Complex in La Vega-Jarabacoa-Janico Area, central Espanola: Geological and Geochemical features of the sea floor during the early stages of evolution, in Mann, P., Draper, G., and Lewis, J., eds., Geologic and Tectonic Development of the North American- Caribbean Plate Boundary in Espanola: Special Paper Geological Society of America, v. 262, p. 115-142.

Litherland, M., Aspden, J., and Jemielita, R.A., 1994, The Metamorphic Belts of Ecuador: British Geological Survey Overseas Memoir 11, 147 p.

Luzieux, L.D.A., 2007, Origin and Late Cretaceous-Tertiary Evolution of the Ecuadorian Forearc [Ph.D. thesis]: Zurich, Switzerland, Institute of Geology, ETH Zurich, 197 p.

Luzieux, L.D.A., Heller, F., Spikings, F., Vallejo, C.F., and Winkler, W., 2006, Origin and Cretaceous tectonic history of the coastal Ecuadorian forearc between 1˚ N and 3˚ S: Paleomagnetic, radiometric and fossil evidence: Earth and Planetary Science Letters, v. 249, p. 400-414.

Macia, C., 1985, Caracteristicas petrograficas y geoquimicas de rocas basalticas de la peninsula de Cabo Corrientes (Serrania de Baudo), Colombia: Geologia Colombiana, v. 14, p. 25-37.

Mahoney, J.J., Storey, M., Duncan, R.A., Spencer, K.J., and Pringle, M., 1993, Geochemistry and geochronology of the Ontong Java Plateau, in Pringle, M., Sager, W., Sliter, W., and Stein, S., eds., Large Igneous Provinces: Continental, Oceanic, and Planetary Flood Volcanism, American Geophysical Union, Geophysical Monograph, v. 100, p. 183-216.

Mamberti, M., Lapierre, H., Bosch, D., Jaillard, E., Ethien, R., Hernandez, J., and Polve, M., 2003, Accreted fragments of the Late Cretaceous Caribbean-Colombian Plateau in Ecuador: Lithos, v. 66, p. 173-199.

Mamberti, M., Lapierre, H., Bosch, D., Jaillard, E., Hernandez, J., and Polve, M., 2004, The Early Cretaceous San Juan plutonic suite, Ecuador: a magma chamber in an Oceanic Plateau: Canadian Journal of Earth Sciences, v. 41, p. 1237-1258.

Marcano, V, 1873, Recuerdos de una exploracion cienifica, I, Los Roques-Cayo de Sal-Cayo de Cocos-Cayode Agua-CayoCarcol-Gran Roque Aspecto General: La Revista, Caracas, v. 3, no. 7, p. 99-101.

Maresch, W.V.B., Stockhert, B., Baumann, A., Kaiser, C., Kluge, R., Kuckhans-Luder, G., Brix, M., and Thomson, S., 2000, Crustal history and plate tectonic development in the Southern Caribbean, in Miller, H., and Herve, F., eds., Geoscientific Cooperation with Latin America, 31st International Geologic Congress, Rio de Janerio 2000: Zeitschrift fur angewandte Geologie Sonderhaft, v. 1, p. 283-290.

Marriner, G.F., and Millward, D., 1984, The petrology and geochemistry of Cretaceous to Recent volcanism in Colombia: The magmatic history of an accretionary plate margin: Journal of the Geological Society, London, v. 141, p. 473-486.

Mauffret, A., and Leroy, S., 1997, Seismic stratigraphy and structure of the Caribbean igneous province: Tectonophysics, v. 283, p. 61-104.

Mauffret, A., Leroy, S., Vila, J.-M.V., Hallot, E., Mercier de Lepinay, B., and Duncan, R.A., 2001, Prolonged magmatic and tectonic development of the Caribbean Igneous Province revealed by a diving submersible survey: Marine Geophysical Researches, v. 22, p. 17-45.

Maurrasse, F., 1990, Stratigraphic correlation for the circum-Caribbean region, in Dengo, G., and Case, J.E., eds., The Caribbean Region: The Geology of North America: Geological Society of America, Boulder, Colorado, p. Plates 4,5.

Maurrasse, F.J., Husler, J., Georges, G., Schmitt, R., and Damond, P., 1979, Upraised Caribbean sea floor below acoustic reflector B at the southern peninsula of Haiti: Geologie Mijnbouw, v. 58, p. 71-83.

McCourt, W.J., Aspden, J.A., and Brook, M., 1984, New geological and geochronological data from the Colombian Andes: continental growth by multiple accretion: Journal of the Geological Society, London, v. 141, p. 831- 845

McCourt, W.J., Duque, P., Pilatasig, L.F., and Villagomez, R., 1998, Mapa geologico de la Cordillera Occidental del Ecuador entre 1°-2° S., escala 1/200000: CODIGEM-Min. Energ. Min.-BGS publs, Quito.

Metti, A., and Recchi, G., 1972, Proyecto Minero Fase III, Geologia de la Peninsula de Sona e Isla de Coiba y reconocimiento geoquimico: Minerales, Ministerio de Comercio e Industrias, Direccion General de Recoursos.

Millward, D, Marriner, G.F., and Saunders, A.D., 1984, Cretaceous tholeiitic volcanic rocks from the Western Cordillera of Colombia: Journal of the Geological Society, London, v. 141, p. 847-860.

Monen, H.P., 1977, Geological map of the Aruba Lava Formation [unpublished M.Sc. Thesis].

Montgomery, H., and Pessagno Jr., E.A., 1999, Cretaceous microfaunas of the Blue Mountains, Jamaica, and of the northern and central basement complexes of Hispaniola, in Mann, P., ed., Caribbean Basins. Sedimentary basins of the world: Elsevier Science B.V., Amsterdam, The Netherlands, p. 237-246.

Mortensen, J.K., and Hulbert, L.J., 1992, A U-Pb zircon age for a Maple Creek gabbro sill, Tatamagouche Creek area, southwestern Yukon Territory: Radiogenic age and isotopic studies: Report 5: Geological Survey of Canada Paper 91-2, p. 175-179.

Nivia, A., 1987, The geochemistry and origin of the Amaime and Volcanic sequences, SW Colombia, [M.Phil. Thesis]: University of Leicester, UK, 164 p.

Ostos, M., 1990, Tectonic evolution of the south-central Caribbean based on geochemical data [Ph.D. dissertation]: Houston, Rice University, 441 p.

Ostos, M., and Sisson, V.B., 2005, Geochemistry and tectonic setting of igneous and metaigneous rocks of northern Venezuela, in Ave Lallemant, H.G., and Sisson, V.B.,

eds., Caribbean-South American plate interactions, Venezuela: Geological Society of America Special Paper 394, p. 119-156.

Palmer, H.C., 1979, Geology of the Moncion-Jarabacoa area, Dominican Republic, in Lidz, B., and Nagle, F., eds., Tectonic Focal Point of the North Caribbean: Miami Geological Society, p. 29-68.

Parrish, R.R., and McNicoll, V.J., 1992, U-Pb age determinations from the southern Vancouver Island area, British Columbia, in Austin, R.L., ed., Conodonts, investigative techniques and applications: Proceeding of the Fourth European Conodont Symposium (ECOS IV): London, U.K., Ellis Norwood, p. 96-121.

Pindell, J.L., and Barrett, S.F., 1990, Geological evolution of the Caribbean region: a Plate tectonic perspective, in Dengo, G., and Case, J.E., eds., The Caribbean Region, The Geology of North America: Geological Society of 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, 179-211.

Pindell, J.L., Kennan, L., Maresch, W.V., Stanek, K.P., Draper, G., and Higgs, R., 2005, Plate kinematics and crustal dynamics of circum-Caribbean arc-continent interactions, and tectonic controls on basin development in proto-Caribbean margins, in Ave-Lallemant, H.G., and Sisson, V.B., eds., Caribbean South American Plate Interactions, Venezuela: Geological Society of America, Special Papers 394, p. 7-52.

Pindell, J., Kennan, L., Stanek, K.P., Maresch, W.V., and Draper, G., 2006, Foundations of Gulf of Mexico and Caribbean evolution: Eight controversies resolved: Geologica Acta, v. 4, p. 303-341.

Pourtier, E., 2001, Petrologie et geochimie des unites magmatiques de la cote equatorienne: imlications geodynamiques: Unpublished DEA thesis, University of Aix-Marseille.

Pratt, W.T., Duque, P., and Ponce, M., 2005, An autochthonous geological model for the eastern Andes of Ecuador: Tectonophysics, v. 399, p. 251-278.

Priem, H.N.A., Andriessen, P.A.M., Beets, D.J., Boelrijk, N.A.I.M., Hededa, E.H., Verdurmen, E.A.T., and Verschure, R.H., 1979, K-Ar and Rb-Sr dating in the Cretaceous island arc succession of Bonaire, Netherlands Antilles: Geologie en Mijnbouw, v. 58, p. 367-373.

Revillon, S., Hallot, E., Arndt, N.T., Chauvel, C., and Duncan, R.A., 2000, A complex history for the Caribbean plateau: petrology, geochemistry, and geochronology of the Beata Ridge, South Hispaniola: The Journal of Geology, v. 108, p. 641-661.

Reynaud, C., Jaillard, E., Lapierre, H., Mamberti, M., and Mascle, G.H., 1999, Oceanic plateau and island arcs of Southwestern Ecuador: their place in the geodynamic evolution of northwestern South America: Tectonophysics, v. 307, p. 235-254.

Richards, M.A., Duncan, R.A., and Courtillot, V.E., 1989, Flood basalts and hot spot tracks. Plume heads and tails: Science, v. 246, p. 103-107.

Richardson, W.P., Okal, E.A., and Van der Lee, S., 2000, Rayleigh-wave tomography of the Ontong Java Plateau: Physics of the Earth and Planetary Interiors, v. 118, p. 29-61.

Rost, M., 1938, Die venezolanischen Inseln Las Aves, Los Roques, Las Orchilas und die Phophoritlagerstatte von Gran Roque: Deutsch. Geol. Gesell. Zeitscher., v. 90, p. 577-596.

Santamaria, F., and Schubert, C., 1974, Geochemistry and geochronology of the southern Caribbean-northern Venezuela plate boundary: Geological Society of America Bulletin, v. 85, p. 1085-1098.

Saunders, A.D., Tarney, J., Kerr, A.C., and Kent, R.W., 1996, The formation and fate of large igneous provinces: Lithos, v. 37, p. 81-95.

Schmidt, J.M., and Rogers, R.K., 2007, Metallogeny of the Nikolai large igneous province (LIP) in southern Alaska and its influence on the mineral potential of the Talkeetna Mountains, in Ridgway, K.D., et al., eds., Tectonic growth of a collisional continental margin: Crustal evolution of southern Alaska, Geological Socieety of America Special Paper 431, p. 623-648.

Schmitt, A.K., Chamberlain, K.R., Swapp, S.M., and Harrison, T.M., 2010, In situ U-Pb dating of micro-baddeleyite by secondary ion mass spectrometry: Chemical Geology, v. 269, p. 386-395.

Schubert, C., and Moticska, P., 1972, Reconocimiento geologico de las islas venezolanas en el Mar Caribe, entre Los Roques y Los Testigos (Dependencias Federales) I: Intrdoccion e islas centrales: Acta Cient. Venezolana, v. 23, no. 6, p. 210-223.

Schubert, C., and Moticska, P., 1973, Reconocimiento geologico de las islas veenezolanas en el Mar Caribe, entre Los Roques y Los Testigos (Dependencias Federales) II: Islas orientales y conclusiones: Acta Cient. Venezolana, v. 24, no. 1, p. 19-31.

Sen, G., Hickey-Vargas, D.G., Waggoner, F., and Maurasse, F., 1988, Geochemistry of basalts from the Dumisseau Formation, southern Haiti: Implications for the origin of the Caribbean Sea crust: Earth Planetary Science Letters, v. 87, p. 423-437.

Sigurdsson, H., Leckie, R.M., Acton, G.D., and ODP Leg 165 Scientific Party, 1997, Site 1001: Proceedings of the Ocean Drilling Program, Initial Reports, Ocean Drilling Project: Texas A&M University, College Station, Texas, v. 165, p. 291-357.

Sinton, C.W., and Duncan, R.A., 1997, Potential links between ocean plateau volcanism and global ocean anoxia at the Cenomanian-Turonian boundary: Economic Geology, v. 92, p. 846-842.

Sinton, C.W., Duncan, R.A., and Denyer, P., 1997, Nicoya peninsula: a single suite of Caribbean oceanic plateau magmas: Journal of Geophysical Research, v. 102, p. 15507-15520.

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.

Sinton, C.W., Sigurdsson, H., and Duncan, R.A., 2000, Geochronology and petrology of the igneous basement at the lower Nicaraguan Rise, Site 1001: Proceedings of the Ocean Drilling Program, Scientific Results, Leg 165: Texas A&M, College Station, Texas, Ocean Drilling Program, p. 233-236.

Sluggett, C.L., Uranium-lead age and geochemical constraints on Paleozoic and early Mesozoic magmatism in Wrangellia Terrane, Saltspring Island, British Columbia: B. Sc. Thesis, Vancouver, University of British Columbia, 84 p.

Smit, J., 1977, Planktonic formaniferal faunas from the upper part of the Washikemba Formation, Bonaire: 8th Caribbean Geological Conference, Willemstad, Curacao, p. 192-193.

Snoke, A.W., Rowe, D.W., Yule, J.D., and Wadge, G., 2001, Petrologic and structural history of Tobago, West Indies: A fragment of the accreted, Mesozoic oceanic-arc of the Southern Caribbean: Geological Society of America Special Paper 354, 54 p.

Snoke, A.W., Yule, J.D., Rowe, D.W., Wadge, G., and Sharp, W.D., 1990, Stratigrahpic and structural relationships on Tobago, West Indies, and some tectonic implications, in

Larue, D.K., and Draper, G., eds., Transactions of the 12th Caribbean geological conference, St. Croix, U.S. Virgin Islands, v. 12: Miami Geological Society, Miami, Florida, p. 389-402.

Snow, L.J., Duncan, R.A., and Bralower, T.J., 2005, Trace element abundances in the Rock Canyon Anticline, Pueblo, Colorado, marine sedimentary section and their relationship to Caribbean plateau construction and ocean anoxic event 2: Paleoceanography, v. 20, p. A3005.

Spadea, P., Espinosa, A., and Orrego, A., 1989, High-Mg extrusive rocks from the Romeral zone ophiolites in the southwestern Colombian Andes: Journal of Geology, vol. 95, p. 377-395.

Spikings, R.A., Winkler, W., Hughes, R.A., and Handler, R., 2005, Thermochronology of allochthonous blocks in Ecuador: Unraveling the accretionary and post-accretionary history of the Northern Andes: Tectonophysics, v. 399, p. 195-220.

Stanek, K.P., Cobiella, J., Maresch, W.V., Millan, G., Grafe, F., and Grevel, C., 2000, Geological development in Cuba, in Miller, H., and Herve, F., eds., Geoscientific Cooperation with Latin America: Zeitschrift fur angwandte Geologie, Sonderheft, v. 1., p. 59-266.

Stockhert, B., Maresch, W.V., Brix, M., Kaiser, C., Toetz, A., Kluge, R., and Kruckhansleuder, G., 1995, Crustal history of Margarita Island (Venezuela) in detail: Constraint on the Caribbean plate-tectonic scenario: Geology, v. 23, p. 787-790.

Storey, M., Mahoney, J.J., Kroenke, L.W., and Saunders, A.D., 1991, Are oceanic plateaux sites of komatiite formation: Geology, v. 19, p. 376-379.

Tarnudo, J.A., Brinkman, D.B., Renne, P.R., Cottrell, R.D., Scher, H., and Castillo, P., 1998, Evidence for extreme climatic warmth from Late Cretaceous Arctic vertebrates: Science, v. 282, p. 2241-2244.

Tarduno, J.A., Sliter, W.W., Kroenke, L.W., Leckie, M., Mahoney, J.J., Musgrave, R.J., Storey, M., and Winterer, E.L., 1991, Rapid formation of the Ontong Java Plateau by Aptian mantle plume volcanism: Science, v. 254, p. 399-403.

Tejada, M.L.G., Mahoney, J.J., Duncan, R.A., and Hawkins, M.P., 1996, Age and geochemistry of basement and alkalic rocks of Malaita and Santa Isabel, Solomon Islands, southern margin of Ontong Java Plateau: Journal of Petrology, v. 37, 361-394.

Tejada, M.L.G., Mahoney, J.J., Neal, C.R., Duncan, R.A., and Petterson, M.G., 2002, Basement geochemistry and geochronology of Central Malaita, Solomon Islands, with implications for the origin and evolution of the Ontong Java Plateau: Journal of Petrology, v. 43, p. 449-484.

Thompson, P. M. E., 2002, Petrology and geochronology of an arc sequence, Bonaire, Dutch Antilles, and its relationship to the Caribbean Plateau, [Ph. D. dissertation]: University of Leicester, Leicester, U.K., 322p.

Thompson, P.M.E., Kempton, P.D., White, R.V., Kerr, A.C., Tarney, J., Saunders, A.D., and Fitton, J.G., 2003, Hf-Nd isotope constraints on the origin of the Cretaceous Caribbean plateau and its relationship to the Galapagos plume: Earth and Planetary Science Letters, v. 217, p. 59-76.

Thompson, P.M.E., Kempton, P.D., White, R.V., Saunders, A.D., Kerr, A.C., Tarney, J., and Pringle, M.S., 2004, Elemental, Hf-Nd isotopic and geochronological constraints on an

island arc sequence associated with the Cretaceous Caribbean plateau: Bonaire, Dutch Antilles: Lithos, v. 74, p. 91-116.

Tistl, M., and Salazar, G., 1994, The tectono-magmatic evolution of northwestern South America: Zentralblatt fur Geologie und Palaontologie, vol. 1-2, p. 439-453.

Vallejo, C., 2007, Evolution of the Western Cordillera in the Andes of Ecuador (Late Cretaceous-Paleogene) [Ph.D. Thesis]: Zurich, Switzerland, Institute of Geology, ETH Zurich, 208 p.

Vallejo, C., Spikings, R.A., Winkler, W., Luqieux, L., Chew, D., and Page, L., 2006, The early interaction between the Caribbean Plateau and the NW South American plate: Terra Nova, v. 18, p. 264-269.

Vallejo, C., Winkler, W., Spikings, R.A., Luzieux, L., Heller, F., and Bussy, F., 2009, Mode and timing of terrane accretioni in the forearc of the Andes in Ecuador, in Kay, S.M., Ramos, V.A., and Dickinson, W.R., eds., Backbone of the Americas: Shallow Subduction, Plateau Uplift, and Ridge and Terrane Collision: Geological Society of America Memoir 204, p. 1-20.

Wadge, T.A., Jackson, T.A., Isaacs, M.C., and Smith, T.E., 1982, The ophiolitic Bath-Dunrobin Formation, Jamaica: significance for Cretaceous plate margin evolution in the northwestern Caribbean, Journal of the Geological Society, London, v. 139, p. 321-333.

Wadge, G., and Draper, G., Structural geology of the southeastern Blue Mountains, Jamaica: Geologie en Mijnbouw, Special Issue, 8th Caribbean Geological Conference (Willemstad, 1977), v. 57, p. 347-352.

Walker, R.J., Storey, M., Kerr, A.C., Tarney, J., and Arndt, N.T., 1999, Implications of in ^{187}Os heterogeneties a mantle plume: evidence from Gorgona Island and Curacao: Geochemica et Cosmochimica Acta, v. 63, p. 713-728.

Weidman, J., 1978, Ammonites from the Curacao Lava Formation, Curacao, Caribbean: Geologie en Mijnbouw, v. 57, p. 361-364.

Westermann, J.H., 1932, The geology of Aruba [Ph.D thesis]: University of Utrecht.

White, R.V., Tarney, J., Kerr, A.C., Saunders, A.D., Kempton, P.D., Pringle, M.S., 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.

Wildberg, H.G.H., 1984, Der Nicoya-komplex, Costa Rica, Zentralamerika: Magmatismus und Genese eines polygenetischen opiolith-komplexes: Munsterche Forschungen zur Geologie und Palaontologie, v. 61, p. 1-115.

Worner, G., Harmon, R.S., and Wegner, W., 2009, Geochemical evolution of igneous rocks and changing magma sources during the formation and closure of the Central American land bridge of Panama, in Kay, S.M., Ramos, V.M., and Dickenson, W.R., eds., Backbone of the Americas: Shallow Subduction, Plateau Uplift, and Ridge and Terrane Collision: Geological Society of America Memoir 204, p. 183-196.

Wright, J.E., and Wyld, S.J., 2004, Aruba and Curacao: Remnants of a collided Pacific Oceanic Plateau? Initial Geologic results from the BOLIVAR Project: EOS Trans, AGU 85, v. 47.

Wright, J.E., and Wyld, Sandra J., in press, Late Cretaceous subduction initiation on the southern margin of the Caribbean plateau: One Great Arc of the Caribbean (?): Geosphere.

APPENDIX A

REDUCED DATA OF IN-SIMS ANALYSES FROM THE LEEWARD ANTILLES

Name	Age (Ma) 206Pb/ 238U	Age (Ma) 206Pb/ 238U	Age (Ma) 207Pb/ 235U	Age (Ma) 207Pb/ 235U	Age (Ma) 207Pb/ 206Pb	Age (Ma) 207Pb/ 206Pb	Correlation of Concordia Ellipses	% Radiogenic 206Pb	% Radiogenic 207Pb	U O2/ U	U O2/ 94Zr2 O	Th O/ U O	204Pb/ 206Pb
BADDELEYITE													
			weighted averages (badd or zirc)						weighted averages (both)				
		1 s.e.		1 s.e.		1 s.e.							
2009_08_15Aug\ AR12-100b@1.ais	95.7	8.6	100.4	28.5	215.5	634	0.407	89.0	33.1	6.7	7.84E+00	0.11	5.66E-03
2009_08_15Aug\ AR12-100elb@1.ais	107	11	113.4	16.7	254.1	240	0.743	96.7	64.8	5.69	7.99E+00	0.03	2.14E-03
2009_08_15Aug\ AR12-102@1.ais	97.9	6.6	101.2	8.66	179.3	123	0.813	98.6	80.7	8.32	1.22E+01	0.07	1.28E-03
2009_08_15Aug\ AR12-105@1.ais	84.0	11.4	60.72	29.3	-1	0.0163	0.278	93.5	39.4	5.05	3.87E+00	0.02	6.79E-03
2009_08_15Aug\ AR12-113@1.ais	98.8	9.7	133.5	23.4	805.8	322	0.571	98.6	84.9	6.2	1.14E+01	0.38	6.29E-03
2009_08_15Aug\ AR12-116b@1.ais	115	7	120.5	8.58	236.7	97.7	0.828	99.2	88.6	8.88	1.26E+01	0.13	8.23E-04
2009_08_15Aug\ AR12-119b@1.ais	89.9	7.2	98.27	12.4	307.1	232	0.641	97.0	67.2	7.11	6.76E+00	0.05	1.46E-03
2009_08_15Aug\ AR12-98@1.ais	117	9	119.8	20.9	170.9	385	0.46	95.5	56.7	7.85	5.53E+00	0.26	3.37E-03
2009_08_15Aug\ AR12-98@2.ais	109	11	162.2	70.5	1041	886	0.404	82.2	29.8	6.76	5.41E+00	0.11	1.02E-02

Mean = 101.8±8.5 [8.3%] 95% conf.
Wtd by data-pt errs only, 0 of 9 rej.
MSWD = 1.7, probability = 0.10

Mean = 99.4±4.5 [4.5%] 95% conf.
Wtd by data-pt errs only, 0 of 15 rej.
MSWD = 1.17, probability = 0.29

Name	Age (Ma) 206Pb/ 238U	Age (Ma) 206Pb/ 238U	Age (Ma) 207Pb/ 235U	Age (Ma) 207Pb/ 235U	Age (Ma) 207Pb/ 206Pb	Age (Ma) 207Pb/ 206Pb	Correlation of Concordia Ellipses	% Radiogenic 206Pb	% Radiogenic 207Pb	U O2/ U	U O2/ 94Zr2 O	Th O/ U O	204Pb/ 206Pb
ZIRCON (Red = Rejected)													
2009_08_15Aug\ AR12-103z@1.ais	*64.5*	*4.1*	*9.981*	*35.5*	*-1*	*0.0253*	*0.376*	*82.7*	*82.7*	*5.2*	*2.84E+00*	*1.02*	*1.02E-02*
2009_08_15Aug\ AR12-107z@1.ais	95.2	4.5	89.6	5.03	-1	0.00167	0.775	98.7	98.7	5.4	3.15E+01	0.42	7.67E-04
2009_08_15Aug\ AR12-120z@1.ais	91.8	7.7	67.33	97.4	-1	0.0504	0.512	62.3	62.3	4.68	2.01E+00	0.26	2.99E-02
2009_08_15Aug\ AR12-122z@1.ais	102	6	87.18	8.93	-1	0.00361	0.561	99.1	99.1	4.86	4.18E+01	1.60	2.04E-04
2009_08_15Aug\ AR12-56z@1.ais	100	6	110.8	9.24	340.7	136	0.731	99.6	99.6	4.3	3.05E+01	1.06	7.94E-04
2009_08_15Aug\ AR12-97z@1.ais	96.4	9.7	109.7	50.3	407.9	1.01E+03	0.435	96.8	96.8	4.04	3.24E+00	1.13	8.53E-03
2009_08_15Aug\ AR12-97z@2.ais	94.6	12.8	64.93	41.6	-1	0.0204	0.343	92.5	92.5	2.76	3.14E+00	0.96	8.55E-03

Mean = 97.3±5.2 [5.4%] 95% conf.
Wtd by data-pt errs only, 0 of 6 rej.
MSWD = 0.34, probability = 0.89

Figure A1: Reduced data from both baddeleyite and zircon analyses of the diabase unit of the Aruba Lava Formation (ALF).

Name	Age (Ma) 206Pb/ 238U	Age (Ma) 206Pb/ 238U	Age (Ma) 207Pb/ 235U	Age (Ma) 207Pb/ 235U	Age (Ma) 207Pb/ 206Pb	Age (Ma) 207Pb/ 206Pb	Correlation of Concordia Ellipses	% Radiogenic 206Pb	% Radiogenic 207Pb	U O2/ U	U O2/ 94Zr2 O	Th O/ U O	204Pb/ 206Pb
BADDELEYITE													
			weighted averages (badd or zirc)						weighted averages (both)				
		1 s.e.		1 s.e.		1 s.e.							
2009_08_15Aug\ CUR-4_b44@1.ais	120	19	183.4	31.8	1114	426	0.265	97.2	77.3	7.01	5.32E+01	0.26	6.58E-03
2009_08_15Aug\ CUR4-105@1.ais	109	6	134.5	62.3	604.9	1.02E+03	0.465	61.0	10.1	11.1	8.39E+00	0.11	2.41E-02
2009_08_15Aug\ CUR4-11@1.ais	122	6	113.7	29	-1	0.0115	0.391	92.6	40.4	12.1	1.59E+01	0.42	5.74E-03
2009_08_15Aug\ CUR4-18@1.ais	121	6	54.65	51.2	-1	0.0199	0.493	88.7	16.7	14	2.48E+01	1.29	5.07E-03
2009_08_15Aug\ CUR4-19@1.ais	103	6	97.57	70.4	-1	0.033	0.580	77.5	15.2	14.5	9.40E+00	0.87	2.04E-02
2009_08_15Aug\ CUR4-19@2.ais	131	9	224.7	78	1373	689	0.480	71.6	21.2	9.2	6.86E+00	0.22	1.98E-02
2009_08_15Aug\ CUR4-24@1.ais	113	8	137	83.4	586.8	1.37E+03	0.364	69.1	13.6	9.29	1.14E+01	0.19	1.66E-02
2009_08_15Aug\ CUR4-94b@1.ais	110	9	185.3	46.5	1304	501	0.345	88.6	44.4	8.68	5.73E+00	0.20	1.75E-02

Mean = 114.7±7.4 [6.5%] 95% conf.
Wtd by data-pt errs only, 0 of 8 rej.
MSWD = 1.5, probability = 0.15

Mean = 112.7±7.3 [6.5%] 95% conf.
Wtd by data-pt errs only, 0 of 9 rej.
MSWD = 1.9, probability = 0.062

ZIRCON (Red = Rejected)													
2009_08_15Aug\ CUR4-58Z@1.ais	*85*	*4*	*80.25*	*11*	*-1*	*0.00591*	*0.372*	*97.1*	*97.1*	*5.34*	*2.70E+01*	*0.19*	*2.30E-03*
2009_08_15Aug\ CUR4-99z@1.ais	102	6	52.91	61.6	-1	0.0284	0.564	68.6	68.6	5.61	1.56E+01	2.40	1.48E-02

Figure A2: Reduced data from both baddeleyite and zircon analyses of diabase from the Curaçao Lava Formation (CLF).

Name	Age (Ma) 206Pb/ 238U	Age (Ma) 206Pb/ 238U	Age (Ma) 207Pb/ 235U	Age (Ma) 207Pb/ 235U	Age (Ma) 207Pb/ 206Pb	Age (Ma) 207Pb/ 206Pb	Correlation of Concordia Ellipses	% Radiogenic 206Pb	% Radiogenic 207Pb	U O2/ U	U O2/ 94Zr2 O	Th O/ U O	204Pb/ 206Pb
BADDELEYITE													
			weighted averages (badd or zirc)						weighted averages (both)				
		1 s.e.		1 s.e.		1 s.e.							
2009_08_15Aug\ BN58-37@1.ais	117	6	120.6	34.8	188.8	681	0.338	82.7	22.4	10.9	1.65E+01	0.14	1.02E-02
2009_08_15Aug\ BN58-38@1.ais	119	10	153.4	112	734.4	1.59E+03	0.434	64.0	11.5	9.63	1.03E+01	0.20	2.07E-02
2009_08_15Aug\ BN58-39@1.ais	107	6	114	11.6	257.8	209	0.538	90.9	38.4	10.2	2.55E+01	0.34	5.71E-03
2009_08_15Aug\ BN58-39@2.ais	106	4	140.5	39.5	764.5	605	0.399	88.1	36.5	13.8	5.50E+01	1.60	7.34E-03
2009_08_15Aug\ CAR9_BN-58_b10@	130	14	133.8	84	196	1.47E+03	0.410	80.3	20.2	6.01	1.74E+01	0.52	1.07E-02
2009_08_15Aug\ CAR9_BN-58_b13@	109	10	48.35	103	-1	0.0444	0.401	58.3	3.3	9.44	9.92E+00	0.48	2.25E-02
2009_08_15Aug\ CAR9_BN-58_b14@	127	12	162.9	29.8	729.2	320	0.679	96.2	66.8	6.93	4.18E+01	0.56	3.16E-03

Mean = 111.6±5.1 [4.6%] 95% conf.
Wtd by data-pt errs only, 0 of 7 rej.
MSWD = 1.15, probability = 0.33

Mean = 102.2±7.7 [7.5%] 95% conf.
Wtd by data-pt errs only, 0 of 12 rej.
MSWD = 3.6, probability = 0.000

ZICRON (Red = Rejected)													
2009_08_15Aug\ BN-58-11za@1.ais	*36.4*	*2.3*	*144.9*	*9.1*	*2798*	*44.7*	*0.914*	*119*	*119*	*4.52*	*5.75E+02*	*2.23*	*1.70E-03*
2009_08_15Aug\ CAR9_BN58b1@1.ais	84.8	4.8	148.8	17.6	1348	204	0.569	96.4	96.4	4.79	2.25E+01	1.40	5.33E-03
2009_08_15Aug\ BN-58-11zb@1.ais	87.2	6.3	128.9	20.9	987.8	299	0.543	101.0	101.0	4.1	1.47E+02	2.96	1.59E-03
2009_08_15Aug\ BN-58-7za@1.ais	96.1	5.3	154.8	28.8	1184	350	0.537	95.0	95.0	5.13	4.80E+01	2.14	5.64E-03
2009_08_15Aug\ BN-58-10z@1.ais	102	7	98.44	22.5	24.91	527	0.413	91.0	91.0	4.11	2.75E+01	0.60	6.56E-03
2009_08_15Aug\ BN-58-7zb@1.ais	102	6	80.24	33.9	-1	0.0156	0.417	92.6	92.6	4.77	8.52E+01	2.67	4.25E-03
2009_08_15Aug\ CAR9_BN58b5@1.ais	*122*	*10*	*499.5*	*111*	*3123*	*319*	*0.994*	*107*	*107*	*20.3*	*1.69E+02*	*3.31*	1.00E-02

Mean = 93±10 [11%] 95% conf.
Wtd by data-pt errs only, 0 of 5 rej.
MSWD = 2.0, probability = 0.098

Figure A3: Reduced data from both baddeleyite and zircon analyses of the Matijs Diabase of Bonaire.

Name	Age (Ma) 206Pb/238U	Age (Ma) 206Pb/238U	Age (Ma) 207Pb/235U	Age (Ma) 207Pb/235U	Age (Ma) 207Pb/206Pb	Age (Ma) 207Pb/206Pb	Correlation of Concordia Ellipses	% Radiogenic 206Pb	% Radiogenic 207Pb	U O2/U	U O2/94Zr2 O	Th O/U O	204Pb/206Pb
ZIRCON (Red = Rejected)			weighted averages (badd or zirc)						weighted averages (both)				
		1 s.e.		1 s.e.		1 s.e.							
2009_08_15Aug\ LR5-45zd@1.ais	*69.4*	*6.6*	*30.32*	*94.8*	*-1*	*0.0629*	*0.814*	*94.0*	*94.0*	*5.07*	*8.02E+00*	*3.87*	*5.88E-04*
2009_08_15Aug\ LR5-48z@1.ais	*75.5*	*4.5*	*27.2*	*27.5*	*-1*	*0.0168*	*0.382*	*93.7*	*93.7*	*4.93*	*1.24E+01*	*1.89*	*3.72E-03*
2009_08_15Aug\ LR5-45z@1.ais	76.9	5.4	47.71	33.6	-1	0.0202	0.43	96.7	96.7	4.22	1.42E+01	2.14	5.30E-04
2009_08_15Aug\ LR5-39z@1.ais	78.3	7.1	56.17	45.4	-1	0.0268	0.435	95.9	95.9	3.75	7.18E+00	2.27	0.00E+00
2009_08_15Aug\ LR5-10z@1.ais	81.2	6.1	9.544	39.5	-1	0.0223	0.362	94.1	94.1	4.18	8.95E+00	2.35	8.20E-04
2009_08_15Aug\ LR5-38z@1.ais	81.8	6.1	23.14	37.2	-1	0.0209	0.366	94.8	94.8	4.06	9.62E+00	2.02	1.14E-03
2009_08_15Aug\ LR5-46z@1.ais	82.2	5.6	70.4	28.1	-1	0.0158	0.419	96.9	96.9	4.51	7.52E+00	1.83	2.15E-03
2009_08_15Aug\ LR5-40z@1.ais	83.4	8.1	58.09	56.2	-1	0.0313	0.46	92.3	92.3	3.55	8.46E+00	2.06	1.41E-03
2009_08_15Aug\ LR5-45ze@1.ais	84.4	7.8	108.2	72.7	669.3	1.40E+03	0.629	99.7	99.7	3.91	7.02E+00	2.13	3.69E-03
2009_08_15Aug\ LR5-24z@1.ais	86.1	5.8	63.59	51.6	-1	0.028	0.547	98.1	98.1	4.9	1.97E+01	2.68	9.78E-04
2009_08_15Aug\ LR5-45zc@1.ais	86.4	6.8	92.44	31.9	251.3	774	0.41	97.3	97.3	3.93	6.04E+00	1.32	1.43E-03
2009_08_15Aug\ LR5-2z@1.ais	88.3	6.7	154.8	28	1352	321	0.541	102	102	4.01	1.14E+01	1.70	2.31E-03
2009_08_15Aug\ LR5-28z@1.ais	89.9	4.0	79.47	24	-1	0.0125	0.421	98.2	98.2	6.11	1.99E+01	1.98	1.37E-03
2009_08_15Aug\ LR5-4za@1.ais	91.3	7.1	124.4	25.2	815.3	391	0.516	102	102	3.81	1.52E+01	1.93	3.70E-04
2009_08_15Aug\ LR5-22z@1.ais	94.2	7.5	57.26	57.6	-1	0.0287	0.436	94.8	94.8	4.55	6.51E+00	1.88	5.55E-03
2009_08_15Aug\ LR5-27z@1.ais	102	6	80.34	19.9	-1	0.009	0.378	98.4	98.4	4.69	2.18E+01	1.59	8.07E-04
2009_08_15Aug\ LR5-36z@1.ais	103	8	85.02	48.5	-1	0.0221	0.419	97.4	97.4	3.9	1.54E+01	1.81	5.83E-04

Mean = 87.0±4.1 [4.7%] 95% conf.
Wtd by data-pt errs only, 0 of 15 rej.
MSWD = 1.4, probability = 0.13

Figure A4: Reduced data from zircon analyses of the gabbro unit of Gran Roque.