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Special Section:
A fresh look at the Caribbean plate geosystems

Key Points:

- We present an overview of the magmatism and metamorphism of the entire Greater Antilles Arc (GAA) convergent margin system
- Prominent age interval from 95 to 60 Ma might relate to strong thermal/metamorphic events associated with the Caribbean Large Igneous Province
- Immobile trace element geochemical data show that the GAA is dominated by mafic igneous rocks

Supporting Information:

Supporting Information may be found in the online version of this article.

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Review of Geochronologic and Geochemical Data of the Greater Antilles Volcanic Arc and Implications for the Evolution of Oceanic Arcs

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Abstract The Greater Antilles islands of Cuba, Hispaniola, Puerto Rico and Jamaica plus the Virgin Islands host fragments of the fossil convergent margin that records Cretaceous subduction (operated for about 90 m.y.) of the American plates beneath the Caribbean plate and ensuing arc-continent collision in Late Cretaceous-Eocene time. The "soft" collision between the Greater Antilles Arc (GAA) and the Bahamas platform (and the margin of the Maya Block in western Cuba) preserved much of the convergent margin. This fossil geosystem represents an excellent natural laboratory for studying the formation and evolution of an intra-oceanic convergent margin. We compiled geochronologic (664 ages) and geochemical data (more than 1,500 analyses) for GAA igneous and metamorphic rocks. The data was classified with a simple fourfold subdivision: fore-arc mélange, fore-arc ophiolite, magmatic arc, and retro-arc to inspect the evolution of GAA through its entire lifespan. The onset of subduction recorded by fore-arc units, together with the oldest magmatic arc sequence shows that the GAA started in Early Cretaceous time and ceased in Paleogene time. The arc was locally affected (retro-arc region in Hispaniola) by the Caribbean Large Igneous Province (CLIP) in Early Cretaceous and strongly in Late Cretaceous time. Despite multiple biases in the database presented here, this work is intended to help overcome some of the obstacles and motivate systematic study of the GAA. Our results encourage exploration of offshore regions, especially in the east where the forearc is submerged. Offshore explorations are also encouraged in the south, to investigate relations with the CLIP.

1. Introduction

The fossil Greater Antilles Arc (GAA), part of the Great Arc of the Caribbean (Burke, 1988), provides an unusual opportunity to examine the complete evolution of an intra-oceanic convergent margin from birth to demise, especially because much of it is exposed above sea-level. Igneous and metamorphic rocks of the GAA (Figure 1) record subduction beneath the Caribbean plate during the Cretaceous and Paleogene spanning about 90 m.y. all through the present ca. 2,000 km length of the convergent margin (e.g., Iturralde-Vinent et al., 2016; Mann et al., 2007; Pindell & Kennan, 2009 and references therein). In most interpretations, the subducting lithosphere corresponds to the North and South American plates separated by the Proto-Caribbean ridge during the GAA lifetime (e.g., Blanco-Quintero et al., 2010; Pindell & Kennan, 2009). Convergence was terminated with the subduction of passive margin sequences (Despaigne-Díaz et al., 2016, 2017; García-Casco, Iturralde-Vinent, & Pindell, 2008); the ensuing soft collision with the margins of the Maya Block and the Bahamas Platform began in Cuba in the Latest Cretaceous (Iturralde-Vinent et al., 2008; van Hinsbergen et al., 2009) and propagated to Hispaniola and further east (e.g., Escuder-Viruete, Pérez-Estaún, Booth-Rea, & Valverde-Vaquero, 2011; Escuder-Viruete, Perez-Estaún, Gabites, & Suarez-Rodriguez, 2011; Mann, 1999; Pindell & Barrett, 1990). After frontal to oblique collision ended in Eocene time, convergence between the Caribbean and North American plates stopped and the western part of the convergent margin (Cuba) accreted to the North American plate. A new transform boundary—the left-lateral Oriente Transform Fault (Rojas-Agramonte et al., 2005, 2008)—and associated formation of the Cayman Trough during the collision (Middle Eocene) - separated Cuba from the Caribbean plate and eastern GAA fragments (Rosencrantz et al., 1988). This was a "soft" collision, so deformation was mostly modest and most of the arc was not disrupted, making the GAA one of Earth's best-preserved fossil oceanic

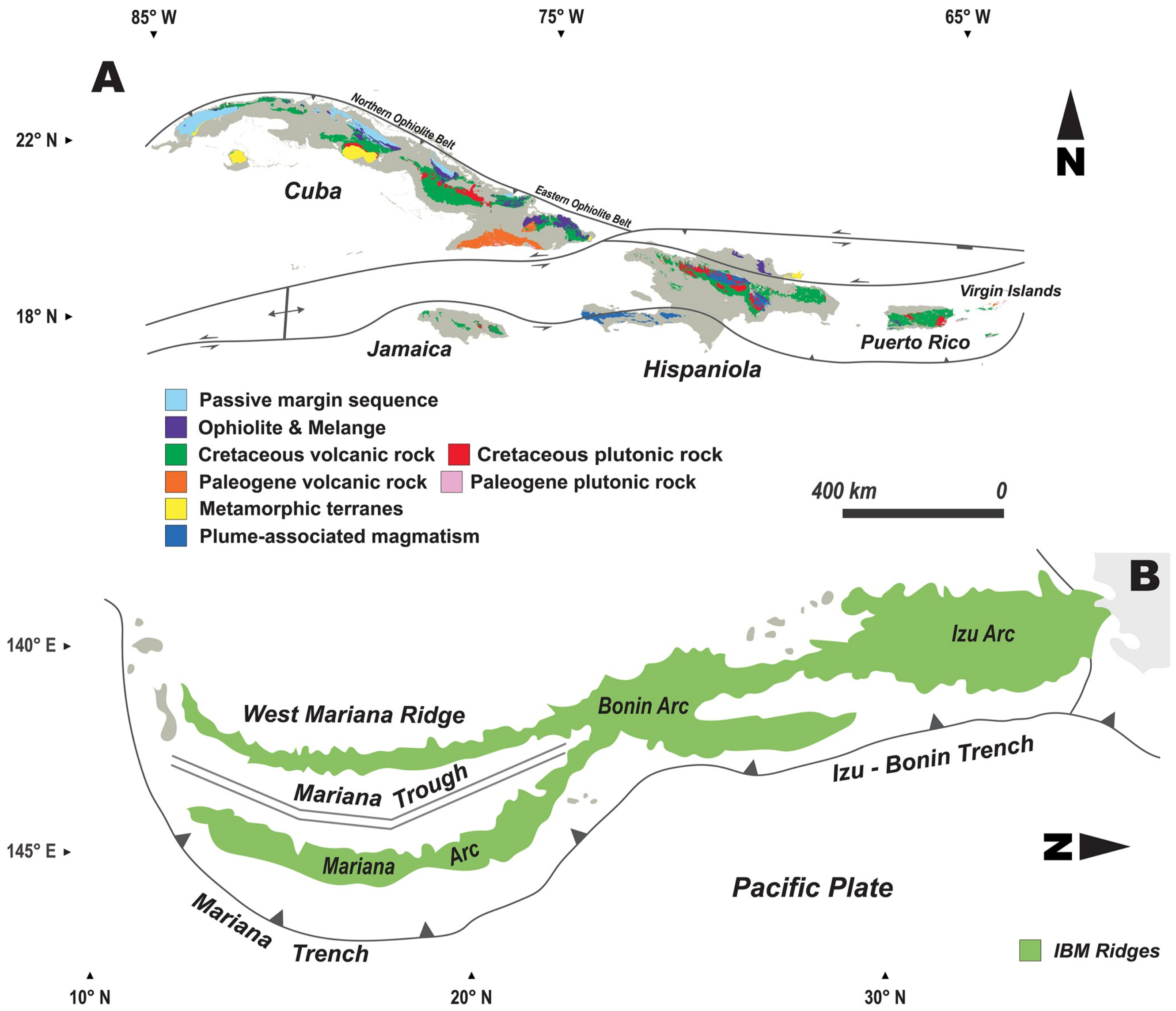

Figure 1. Comparison of fossil and active arcs, at the same scale. (a) Map of the Greater Antilles showing the location of passive margin sequences, ophiolites and melange blocks, magmatic arcs, metamorphic terranes and plume-associated igneous rocks, modified from Torró, Proenza-Fernández, et al. (2016) and Wilson et al. (2019). (b) Tectonic map of the Izu-Bonin-Mariana arc system, modified after Stern and Bloomer (1992).

convergent margins. In fact, the GAA is still an active convergent margin east of the Dominican Republic, where slow, highly oblique convergence with Atlantic oceanic lithosphere continues today (e.g., Mann et al., 2002).

The GAA evolved as an intra-oceanic convergent margin; a contemporary analog is the Izu-Bonin-Mariana (IBM) arc system (Figure 1c; Stern et al., 2012) which is mostly submerged. GAA sedimentary, metamorphic and magmatic units developed in subduction-related (fore-arc, arc and retro-arc) environments. These are recognized as follows: (a) extended passive margins of the Bahamas and the Maya Block accreted to the overriding plate in Cuba, (b) ophiolites and ophiolitic mélanges, and (c) magmatic arcs (Cretaceous and Paleogene). Plume-associated igneous rocks were also developed in the GAA retro-arc region. These four tectonic units are not developed on every island, but volcanic rocks are exposed on each.

Previous reviews focused on a range of related issues including the larger geodynamic evolution of the Caribbean plate (e.g., Boschman et al., 2014; Pindell et al., 2005, 2012); terrane accretion history (e.g., García-Casco, Iturralde-Vinent, & Pindell, 2008), the geology of Cuba (e.g., Iturralde-Vinent et al., 2016), high-pressure metamorphism in Cuba (e.g., García-Casco et al., 2006), ophiolitic units (Lewis et al., 2006) and GAA arc igneous rocks (e.g., Lidiak & Anderson, 2015; Lidiak & Jolly, 1996). This paper is the first systematic overview of the magmatism and metamorphism of the entire GAA convergent margin system.

Here, we summarize published petrologic, geochronological, and geochemical data for GAA ophiolites, mélange blocks, the magmatic arc, and retro-arc extensional features and use this information to provide new insights into GAA evolution. We also suggest some potentially fruitful directions for future study. Our approach is to use geochronologic and geochemical data to constrain the entire magmatic and metamorphic history of the convergent margin, from subduction initiation (SI) through maturity and death. The reconstruction does not include other important geological issues, such as deformation, sedimentation, etc. We have two goals in this paper: First, we want to explore if SI models (Stern & Gerya, 2018) are useful for understanding GAA evolution, using the general approach of Hu and Stern (2020). Second, we hope to motivate further systematic study of the GAA convergent margin system.

2. Methods

We imposed a simple fourfold tectonic subdivision on the GAA based on a SW dipping subduction system agreed to by most scholars working in the Caribbean (e.g., Boschman et al., 2014; Escuder-Viruete, Diaz de Neira, et al., 2006; Escuder-Viruete, Contreras, Stein, et al., 2007; García-Casco et al., 2006; García-Casco, Iturralde-Vinent, & Pindell, 2008; Pindell & Kennan, 2009; Pindell et al., 2005; Rojas-Agramonte et al., 2021). In addition we used modern geographic relationships of rock units relative to the present position of the magmatic arc to put published data about GAA rocks into 4 tectonic domains: (a) forearc mélange; (b) forearc ophiolite; (c) magmatic arc (Cretaceous and Paleogene); and (d) retro-arc region, including metamorphic terranes and igneous rocks. This subdivision does not strictly correlate with the geotectonic position of the different geologic complexes in the Cretaceous to their present geographic positions, but it is a useful approximation. Geochronological and geochemical data published in the peer-reviewed literature for Cuba, Hispaniola, Puerto Rico, Jamaica, and the Virgin Islands were assigned into one of the four present tectonic subdivisions (Figure 2).

The compiled units are listed in Table S1. The geochronological compilation was done after Wilson et al. (2019) and includes a total of 664 samples including 2 paleontologically constrained lava flow ages and 662 radiometric ages determined by six dating techniques: K-Ar (329 samples, 49.5% of data), U-Pb zircon (138 samples, 20.8% of data), ^{40}Ar-^{39}Ar (168 samples, 25.3% of data), Rb-Sr (14 samples, 2.1% of data), Re-Os (6 samples, 0.9% of data), and Lu-Hf (7 samples, 1.1% of data). These age data are compiled from 92 studies. A total of 1,537 geochemical analyses were compiled from 51 studies. Samples were screened to avoid highly altered samples using loss on ignition (LOI); only samples with less than 4 wt.% LOI (1,185 samples, Figure 3) were selected, then further filtered to remove samples with no trace element data, leaving 1,112 samples for plotting on trace element diagrams. Immobile trace element plots were used to classify lithologies and to distinguish the tectonic affinities of GAA felsic and mafic components. For the purposes of plotting on tectonic discrimination diagrams, lithologies classified as basalt, basalt-andesite, and alkali basalt are plotted as “mafic”; all other lithologies including dacite/rhyolite, trachy-andesite, and trachyte are classified as “felsic.” Details of geochronological data and sources are provided in the supplementary documents (Tables S1 and S2) and listed in the references.

3. Results

Below we first explain the fourfold subdivision of the GAA (Section 3.1), then what age data was compiled and filtered (Section 3.2), and finally how immobile trace element data was compiled and filtered (Section 3.3).

3.1. Fourfold Subdivision of the Greater Antilles Arc

In northern Cuba extensive relics of oceanic lithosphere are recognized as the “northern ophiolites” and “eastern ophiolites” (Iturralde-Vinent, 1998; Iturralde-Vinent et al., 2006). This forms a discontinuous belt of outcropping ophiolites that can be traced more than 1,000 km from Cajálbana in the west to Baracoa in the east (Figures 1a and 4). Three main segments with seven major exposures can be distinguished along strike, from west to east: Cajálbana represents the western segment; the central segment is represented by Havana-Matanzas, Villa Clara, Camagüey, and Holguín; while Mayarí-Cristal and Moa-Baracoa make up the eastern segment. The ophiolite belt lies north of the magmatic arc and overthrusts sedimentary rocks of the North American continental margin

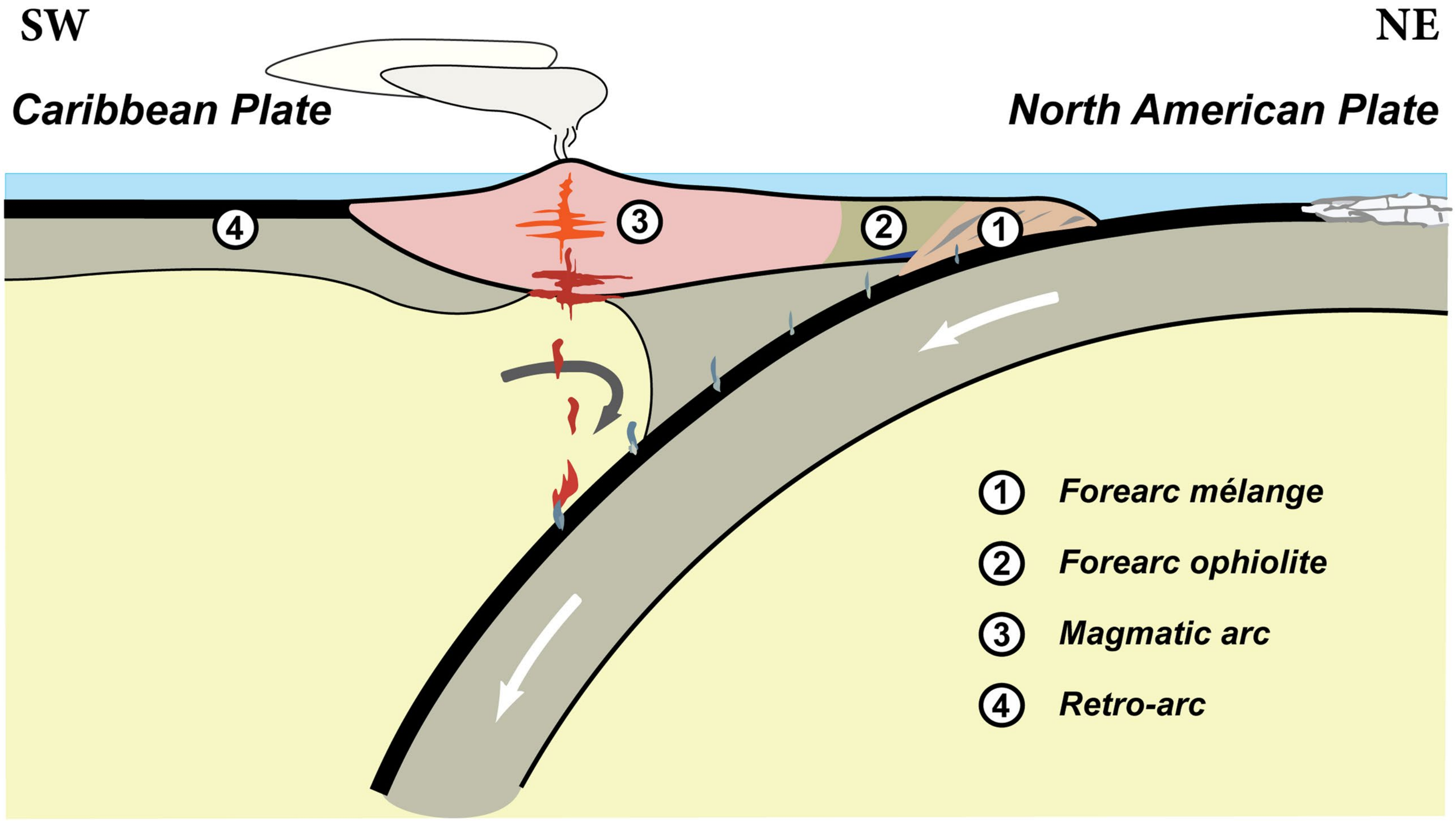

Figure 2. Simplified cross-section of the Greater Antilles Arc during Cretaceous times showing present-day location of geologic bodies in the fourfold subdivision discussed here with respect to the location of the magmatic arc.

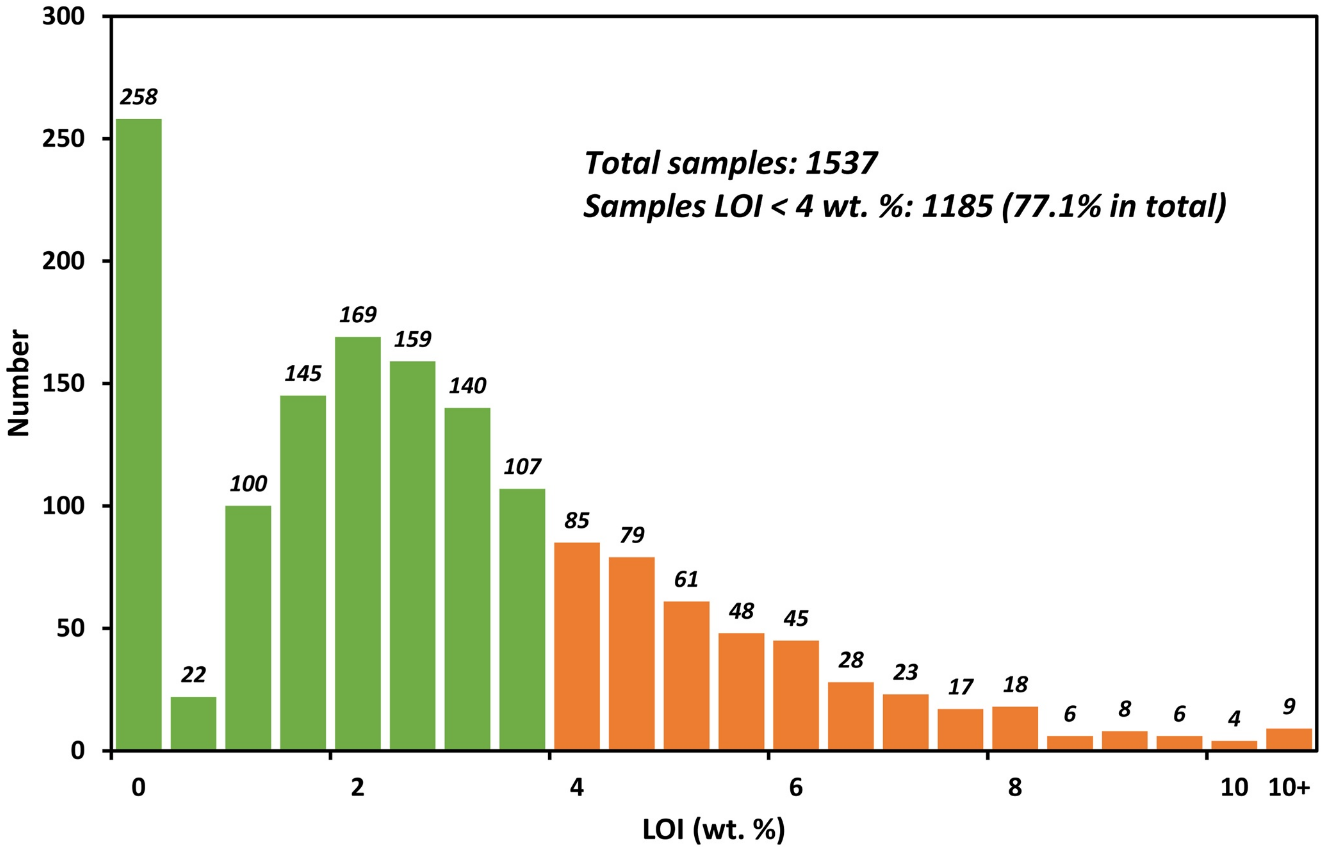

Figure 3. Histogram of loss on ignition from compiled Greater Antilles Arc geochemical data.

in western and central Cuba, revealing that they formed in what became the forearc. Ophiolites in the eastern segment are tectonically emplaced from the SW on top of the Cretaceous volcanic arc, in contrast to other massifs of the western and the central segments. Hence, there is doubt as to whether this segment represents a forearc or formed in a back-arc environment (Marchesi et al., 2006, 2007). A few ophiolitic slices are also present in the geographic rear-arc setting in the Escambray massif to the south of the magmatic arc which likely represent fragments of the subducted Protocaribbean ocean or Caribbean forearc (García-Casco et al., 2006, and references therein). García-Casco et al. (2006) noted the contrasting petrologic evolution of high-pressure metamorphic complexes within mélange between the eastern segment and western-central segments (clockwise vs.

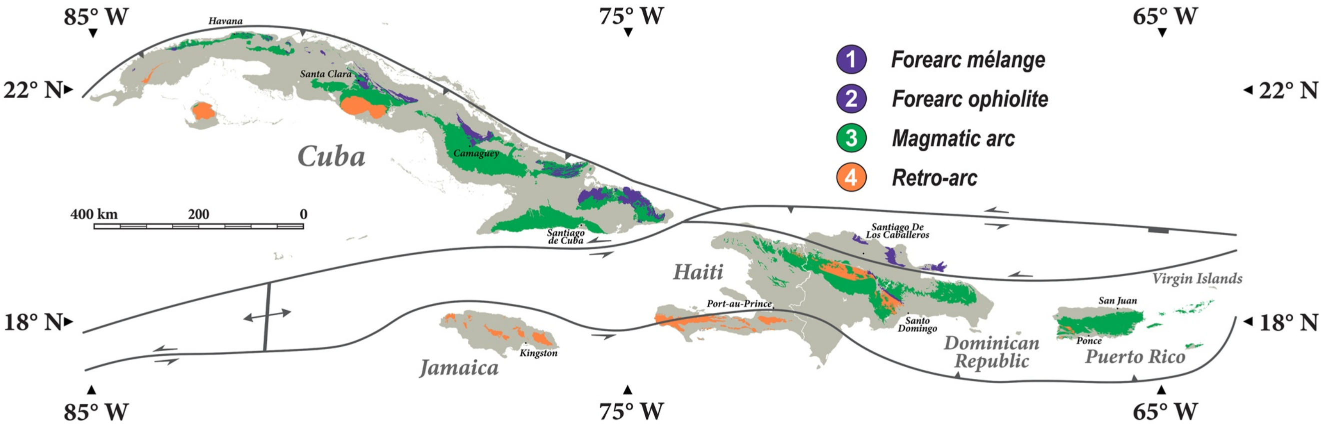

Figure 4. Simplified tectonic map of the Greater Antilles Arc showing the location of geologic units in the fourfold subdivision. See text for further discussion.

counterclockwise P-T path), as a likely consequence of timing of subduction-accretion and tectonic setting of formation (onset of subduction vs. mature subduction) (Blanco-Quintero et al., 2010; Blanco-Quintero, Gerya, et al., 2011; García-Casco, Lázaro, et al., 2008; Lázaro et al., 2009).

Forearc ophiolites refer to the massifs of Cajálbana, Havana-Matanzas, Santa Clara, Camagüey, and Holguín within the northern ophiolite belt. For simplicity, the eastern ophiolite belt (Mayarí-Baracoa) and its volcanic and plutonic sequences are also included here as an apparent forearc ophiolite. High-pressure metamorphic rocks within serpentinite mélange intermingled with ophiolitic massifs, such as mélange in Cajálbana (in olistostromes) and Habana-Matanzas-Villa Clara and mélange associated with the eastern ophiolite belt, are assigned to the forearc mélange belt. Magmatic arc units include island arc tholeiites and calc-alkaline suites, and alkaline magma hybridized calc-alkaline rocks (Torró et al., 2020 and references therein). These plutonic and volcanic arc rocks include the Cretaceous arc south of the northern ophiolite belt and Paleogene igneous rocks of the Sierra Maestra of southeastern Cuba. The Mabujina arc-related complex (Rojas-Agramonte et al., 2011), and the subducted passive margin-related Pinos, Cangre and Escambray metamorphic terranes (Despaigne-Díaz et al., 2016, 2017; García-Casco et al., 2001; García-Casco, Iturralde-Vinent, & Pindell, 2008) exposed south of the magmatic arc are assigned to the retro-arc based on their present geographic position.

In northern Hispaniola, ophiolites associated with the accretionary complex are present in the Cordillera Septentrional-Samaná Peninsula in the Dominican Republic. These fragments of oceanic lithosphere are part of the Puerto Plata ophiolitic complex (Escuder-Viruete et al., 2014; Hernaiz Huerta et al., 2012) and the Río San Juan metamorphic complex (Escuder-Viruete & Pérez-Estaún, 2006, 2013; Escuder-Viruete, Friedman, et al., 2011; Escuder-Viruete, Pérez-Estaún, Booth-Rea, & Valverde-Vaquero, 2011; Escuder-Viruete, Perez-Estaún, Gabites, & Suarez-Rodriguez, 2011; Escuder-Viruete, Valverde-Vaquero, Rojas-Agramonte, Gabites, Carrion Castillo, & Perez-Estaun, 2013; Escuder-Viruete, Valverde-Vaquero, Rojas-Agramonte, Gabites, Pérez-Estaún, 2013; Krebs et al., 2008, 2011) which include the Río San Juan high-pressure serpentinite mélange and Gaspar Hernández serpentinized peridotite. Escuder-Viruete and Castillo-Carrión (2016) suggested that the high-pressure Cuaba mafic gneisses and amphibolites of the southern Río San Juan metamorphic complex represent exhumed subducted GAA fore-arc, while (ultra-) high-pressure ultramafic rocks from the Cuaba subcomplex are considered to be arc cumulates (Hattori et al., 2010) or mantle plume fragments in an ultra-high pressure oceanic complex (Abbott & Draper, 2007, 2013; Gazel et al., 2011). High-pressure accretionary wedge materials within the Cordillera Septentrional are assigned to the fore-arc mélange. The Punta Balandra unit of the Samaná complex consists of eclogite- and blueschist-interleaved sepentinitic mélange thrust over non-eclogitic units that represent the subducted passive margin (Escuder-Viruete & Pérez-Estaún, 2006); this is assigned to the fore-arc mélange subdivision. Island arc tholeiites and calc-alkaline series igneous rocks are exposed in the Central and Eastern Cordilleras, including volcanic rocks from the Early Cretaceous Los Ranchos and Maimón formations and Tireo group and granitoids which are included in the volcanic arc unit (Escuder-Viruete, Contreras, Stein, et al., 2007; Escuder-Viruete, Diaz de Neira, et al., 2006; Torró, Garcia-Casco, et al., 2016; Torró, Proenza, Marchesi, et al., 2017). Igneous rocks associated with arc-rifting and back-arc spreading in central Hispaniola, and Caribbean Large Igneous Province (CLIP)-associated units such as the Duarte Complex (Dominican Republic) and Dumisseau formation (Haiti and southwestern Dominican Republic) are assigned to the retro-arc (Escuder Viruete et al., 2008; Escuder-Viruete, Joubert, et al., 2016; Escuder Viruete, Perez-Estaún, et al., 2007; Escuder-Viruete, Perez-Estaún, et al., 2011; Sen et al., 1988; Sinton et al., 1998).

Cretaceous and Paleogene volcanic and plutonic rocks of Jamaica (Mitchell, 2020 and references therein), Puerto Rico (e.g., Jolly et al., 1998, 2002, 2008a), and the Virgin Islands (e.g., Jolly & Lidiak, 2006; Lidiak & Jolly, 1998) are included in this study. Jamaican rocks are assigned to the retro-arc. The southern wall of Puerto Rico Trench comprises schists and serpentinites of a submerged accretionary prism (Perfit et al., 1980b). Ophiolitic mélange and peridotite belts of southwestern Puerto Rico (Lidiak et al., 2011; Schellekens, 1998a) belong to the retro-arc region in the fourfold subdivision according to its current geographic location.

3.2. Age and Technique Distribution in the Greater Antilles

A systematic difference in ages occurs between different techniques shown in Figure 5a. For example, U-Pb zircon ages display an older mean of 92 ± 53 (2σ) Ma compared to younger mean ages from Ar-Ar (74 ± 41 Ma) and K-Ar (70 ± 41 Ma) systems. These results indicate that a significant number of Ar-Ar and K-Ar ages represent

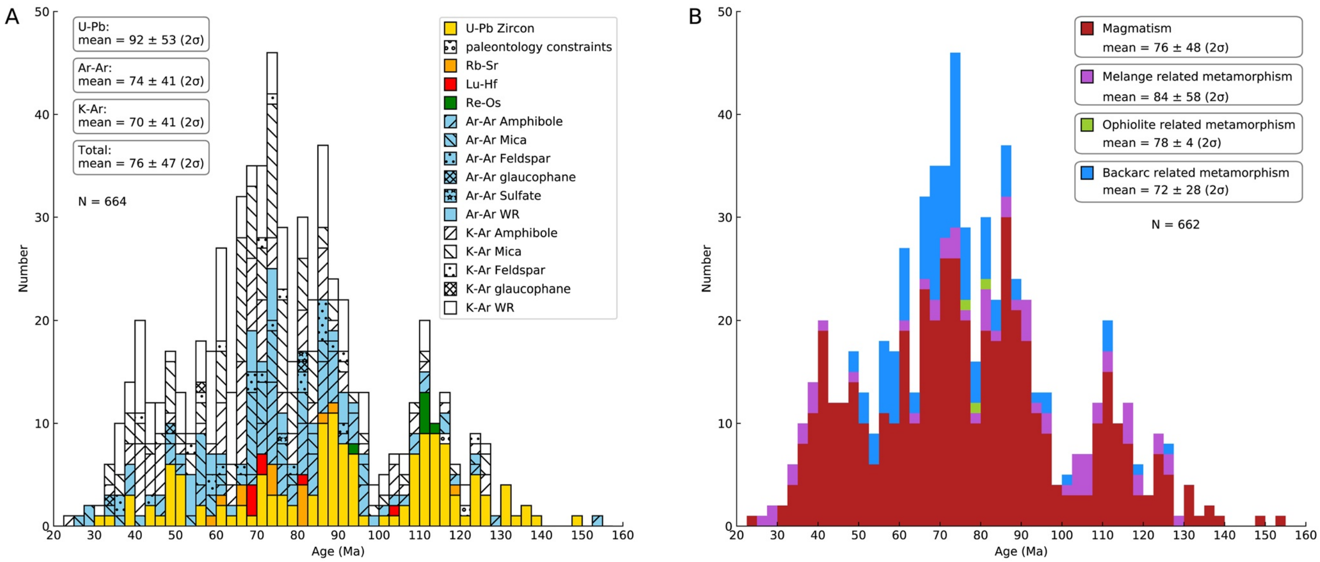

Figure 5. Histogram of compiled age data for the Greater Antilles Arc (GAA), including Cuba, Hispaniola, Jamaica, Puerto Rico, and Virgin Islands sorted by (a) geochronologic method and (b) magmatism and metamorphism (based on association to melange, ophiolite or retro-arc). Results of radiometric dating and paleontology age constraints show the temporal spectrum of the GAA magmatic and metamorphic events. Ages range from 155 Ma (Jurassic) to 30 Ma (Oligocene), but the vast majority (except for two dates) are Cretaceous and Paleogene. Data sources listed in Table S1.

cooling or reset ages, which is particularly evident in the case of Cenozoic K-Ar ages of Cretaceous volcanic arc igneous rocks in Cuba, for example. Figure 5b distinguishes ages determined for igneous versus metamorphic rocks. Metamorphic rocks are further divided into mélange-related metamorphism, ophiolite-related metamorphism, and metamorphism of present-day complexes located in the retroarc (see further discussion in Section 4.4). Melange-related metamorphic ages show an older mean of 84 ± 58 Ma compared to ophiolite-related metamorphic ages (78 ± 4 Ma) and metamorphic ages of present-day retroarc (72 ± 28 Ma). Igneous ages (76 ± 48 Ma) are similar to these two younger metamorphic ages. As mentioned in the geographic sampling bias section, the Caribbean realm is under sampled in many regions and caution must be taken when interpreting age histograms.

Some peaks stand out in the histograms, especially in the Late Cretaceous - early Paleocene from 95 to 60 Ma (Figure 5b). This interval is shown in both igneous and metamorphic rocks and is especially clear in ^{40}Ar/^{39}Ar ages and K-Ar ages. Two subordinate peaks are observed at 120-110 Ma and ~40 Ma. The older peak is especially clear in U-Pb zircon and Re-Os ages and reflects both magmatic and metamorphic activity, including partial melting of metamorphic rocks in a hot subduction zone (eastern Cuba). The younger peak is dominated by K-Ar and ^{40}Ar/^{39}Ar ages and mostly reflects igneous activity. These differences are good examples of technique bias (the difference between ages from different techniques) and potential resetting of the K-Ar isotopic system. There is also geologic bias, the difference between U-Pb zircon, which mostly is used for dating igneous crystallization, and ^{40}Ar/^{39}Ar, which is often used for dating metamorphic and cooling events below ca. 400°C. These biases are discussed further in Section 4.1.

In the next sections, we examine the age distributions of the four tectonic units: forearc ophiolite, forearc mélange, magmatic arc, and retro-arc.

3.2.1. Forearc Mélange

Age data of the forearc mélange in Cuba and Hispaniola come from high-pressure metamorphic rocks within serpentinite mélange, presumably reflecting the GAA subduction zone metamorphic history (Figure 6). Ninety-three dates or 14.0% of the 664 ages in our compilation are for this tectonic subdivision. Some of these are ages of igneous protoliths (esp. U-Pb zircon ages), whereas many others are metamorphic. In Cuba, samples are from mélange intermingled with ophiolites within the northern ophiolite belt and mélanges of Sierra del Convento and La Corea in the Eastern Moa-Baracoa Ophiolite. In northern Hispaniola, ages of high-pressure metamorphic rocks and tectonic blocks of serpentinized peridotite within the Río San Juan serpentinite mélange and Samaná complex are included. In the Puerto Rico Trench, a mica-epidote schist and muscovite from a greenschist yield

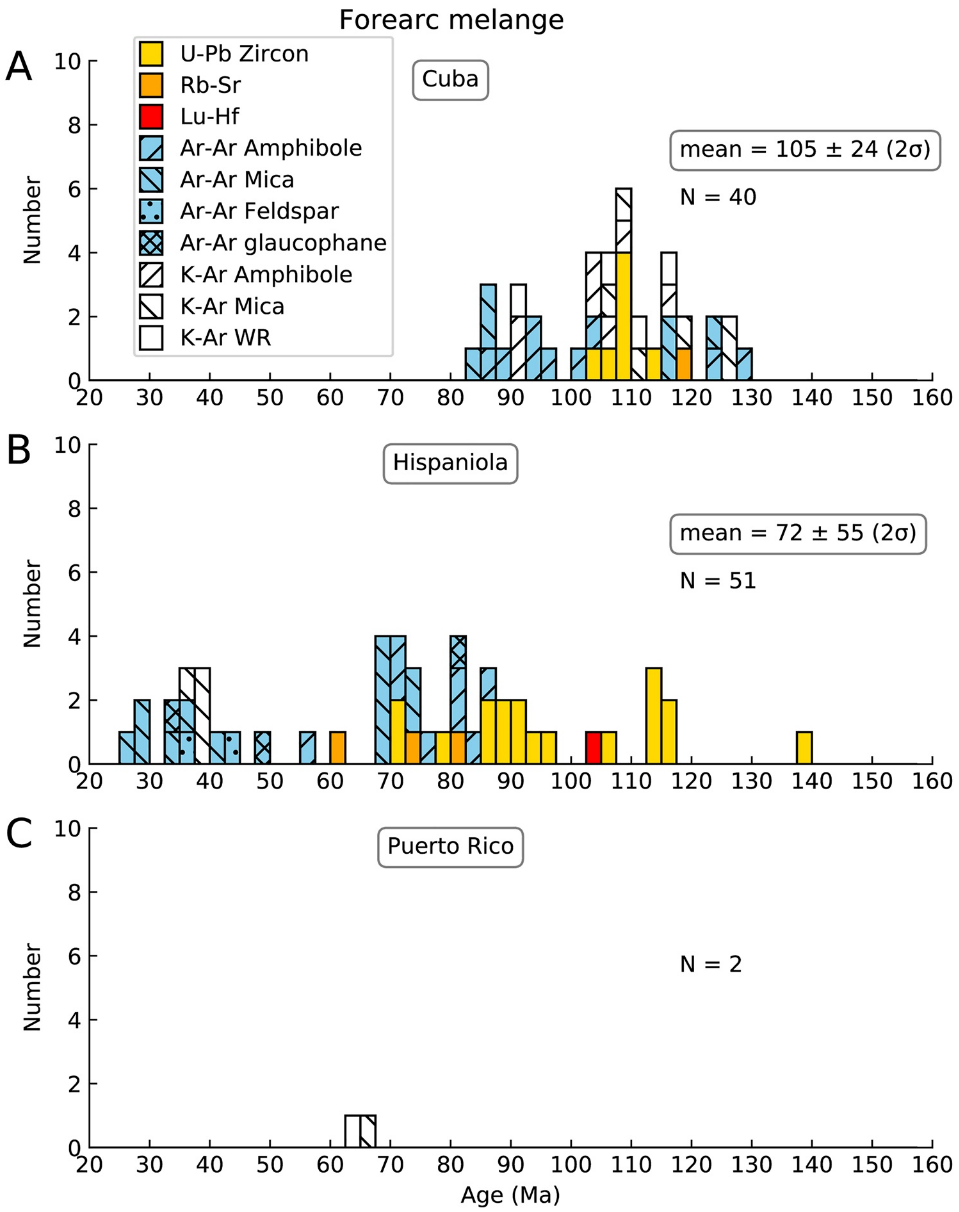

Figure 6. Histogram of compiled age data for forearc melange in the Greater Antilles Arc fourfold subdivision, (a) Cuba, (b) Hispaniola, and (c) Puerto Rico. See text for further discussion.

K-Ar ages of 63 ± 3 Ma and 66 ± 6 Ma (Perfit et al., 1980b). Age distributions of forearc mélange in Hispaniola display a younger mean (72 Ma), larger 2σ (±52 Ma), and a wider range (139–26 Ma) compared to an older mean (105 Ma), smaller 2σ (±24 Ma), and narrower range (130–83 Ma) of Cuba. The possible significance of the difference in ages is explored in the discussion.

3.2.2. Forearc Ophiolite

GAA forearc ophiolites are exposed between the trench (the suture zone in the west and Puerto Rico Trench in the east) and the magmatic arc, mainly exposed in tectonically uplifted regions in Cuba and Hispaniola (Figure 4). There are limited data for Cuba ($N = 22$) and Hispaniola ($N = 8$; Figure 7); only 4.6% of available ages are for this tectonic subdivision. Hispaniola shows older forearc ophiolite ages than Cuba. Within the Rio San Juan metamorphic complex, an evolved gabbro sill intruded into the Gaspar Hernandez serpentinized peridotite-tectonite yielded a concordant zircon U-Pb age of 136.4 ± 0.34 Ma and an even older hornblende ^{40}Ar-^{39}Ar age

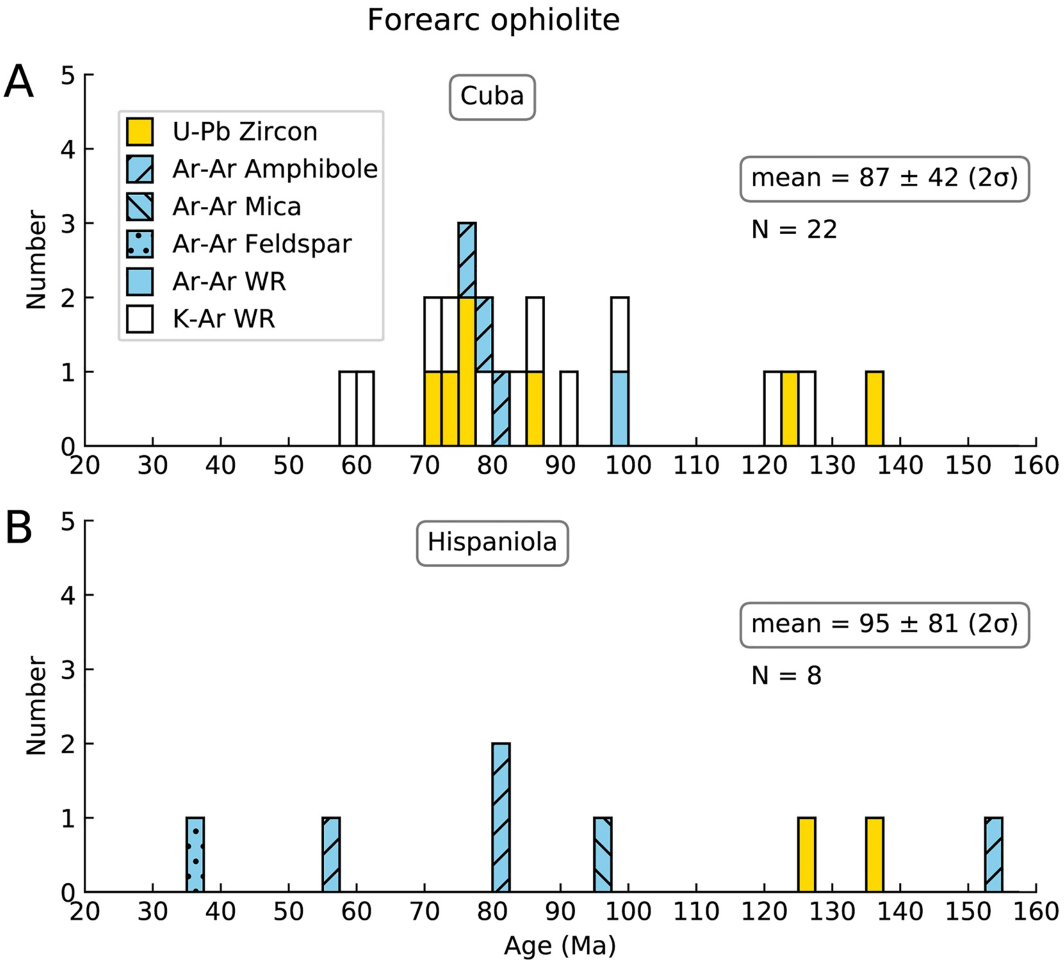

Figure 7. Histograms of compiled age data for forearc ophiolite in (a) Cuba and (b) Hispaniola.

of 153.5 ± 8.9 Ma (Escuder-Viruete, Friedman, et al., 2011). One zircon $^{206}Pb/^{238}U$ age of 126.1 ± 0.3 Ma for an olivine gabbro from the Puerto Plata ophiolitic complex (Monthel, 2010) shows a similar age to the oldest forearc ophiolite ages in Cuba (Lázaro et al., 2016). Ophiolite ages show a wider range, from 127 to 60 Ma, in the northern ophiolite belt in central and western Cuba. In the Havana-Matanzas section, one whole rock ^{40}Ar-^{39}Ar age of 98.1 ± 0.5 Ma was reported for a plagiogranite (Llanes Castro et al., 2019). Ages of intrusive (arc-related) tonalitic and granitic rocks within the Villa Clara ophiolite range from 85 to 61 Ma (Iturralde-Vinent et al., 1996; Rojas-Agramonte et al., 2010), and ages of dolerite and basalt in the Holguín ophiolite range from 127 to 72 Ma (Iturralde-Vinent et al., 1996). In the eastern ophiolite belt, one gabbro sample in the Moa massif yielded a zircon $^{206}Pb/^{238}U$ age of 124.3 ± 0.9 Ma (Rojas-Agramonte et al., 2016) and the Río Grande intrusive in the Mayarí-Cristal ophiolitic massif provided a hornblende ^{40}Ar-^{39}Ar age of 89.70 ± 0.50 Ma (Proenza et al., 2006). Lázaro et al. (2015) reported hornblende ^{40}Ar-^{39}Ar age of 77–81 Ma obtained for amphibolites from the Güira de Jauco metamorphic sole. Thus, forearc ophiolites and metamorphic soles in Cuba and Hispaniola both yield a wide range of ages reflecting varied geodynamic processes affecting the oceanic lithosphere since its formation in the Early Cretaceous.

3.2.3. Magmatic Arc

Age data for GAA Cretaceous and Paleogene magmatic arcs come from Cuba, Hispaniola, Puerto Rico, and the Virgin Islands (Figure 8). Volcanic and plutonic rocks from the Cretaceous and Paleogene arcs are included; 373 ages or 56.2% of the 664 ages in our compilation are for this unit. Magmatism in these four islands shows a broadly similar range but with very different distributions. A strong early peak in magmatism (120–110 Ma) is shown in Hispaniola; this peak is robust because it is dominated by U-Pb zircon ages. A few ages in this range

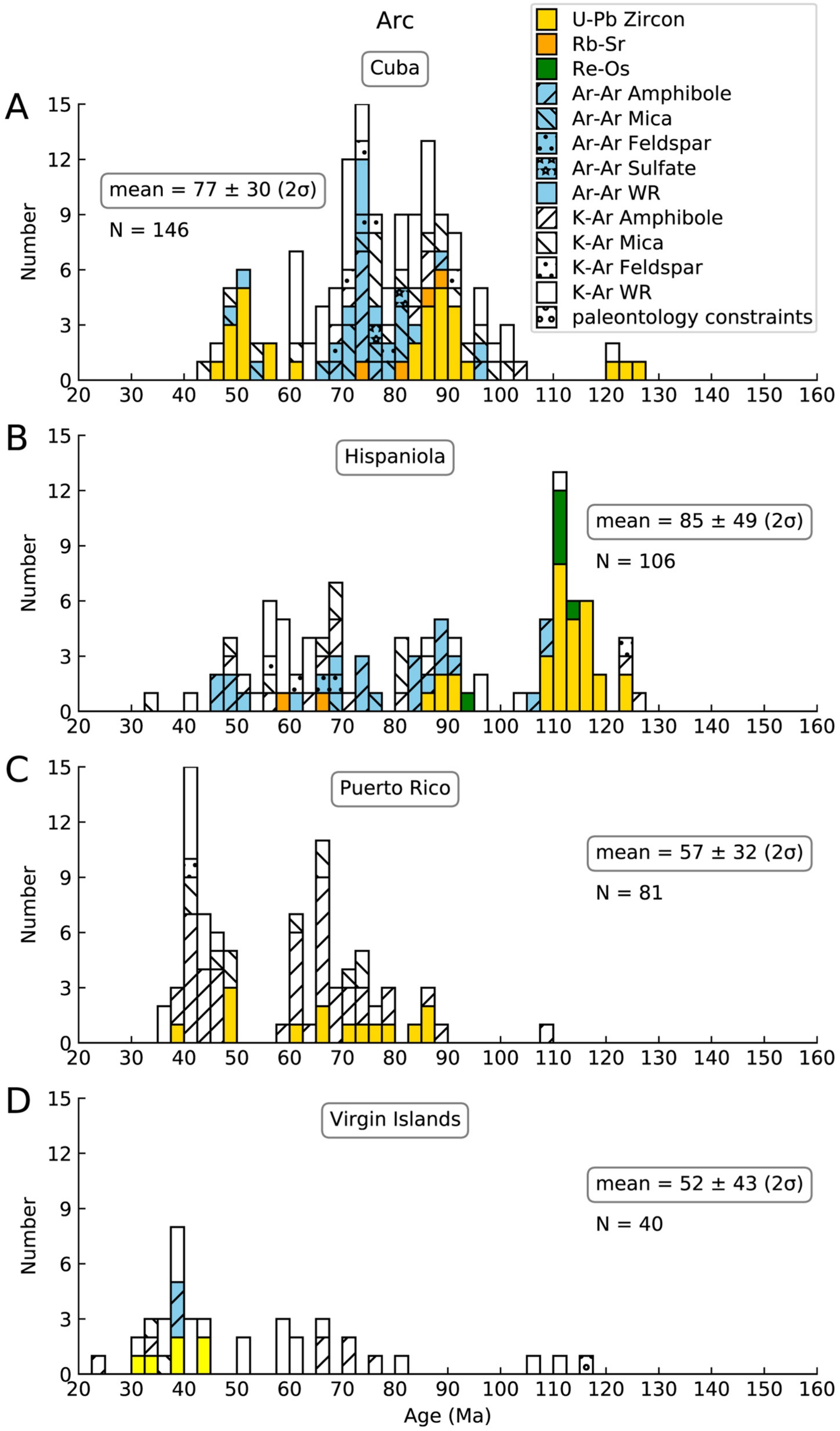

Figure 8. Histogram of compiled age data for the Greater Antilles Arc magmatic arc in (a) Cuba, (b) Hispaniola, (c) Puerto Rico, and (d) Virgin Islands.

are found in Cuba but the main peak is around 90 to 70 Ma. Puerto Rico and Virgin Islands show mostly much younger ages, mostly 75–40 Ma in Puerto Rico and 45-30 Ma in the Virgin Islands. This is a good example of geographic bias. The oldest mean age (85 ± 49 Ma) is found for Hispaniola, and lower mean ages of 77 ± 30 Ma are found for Cuba, 57 ± 32 Ma for Puerto Rico, and 52 ± 43 Ma for the Virgin Islands. The possible significance of the difference in ages is explored in the discussion.

3.2.4. Retro-Arc

The retro-arc subdivision encompasses igneous and metamorphic samples from the region south of the GAA magmatic arc. This subdivision includes magmatic and metamorphic events (Figure 9). Age data of the retro-arc region in Cuba include igneous and metamorphic rocks of the passive margin-related Pinos and Escambray metamorphic terranes and the volcanic arc-related Mabujina complex in western and central Cuba. One-hundred sixty eight ages or 25.3% of the 664 ages in our compilation are for this unit. The metamorphic and magmatic age of the Cuban retro-arc region ranges from 132 to 50 Ma and peak at around 75 to 65 Ma, giving a mean of 74 ± 34 Ma (2σ). In Hispaniola, the retro-arc region consists of oceanic plateau (Escuder-Viruete, Joubert, et al., 2016; Sen et al., 1988) and transitional and oceanic crust, which formed during Late Cretaceous back-arc basin opening (Escuder-Viruete et al., 2008). The age of Hispaniola retro-arc samples ranges from 126 to 53 Ma, with a peak around 90 Ma and a mean of 90 ± 28 Ma (2σ).

In the southwestern corner of Puerto Rico, the Bermeja Complex lies behind (south of) the Cretaceous magmatic arc. Two samples from Las Palmas Amphibolite provide hornblende K-Ar ages of 126 ± 3 Ma and 112 ± 15 Ma (Cox et al., 1977). Zircons from amphibolite boulders in the Bermeja complex show older ages (ca. 130 Ma; Pérez, 2008).

Jamaica falls in the GAA retro-arc region due to its location well to the south and west of the magmatic arc in Cuba and Hispaniola, respectively. Metamorphic and magmatic rocks in Jamaica range in age from 120 to 53 Ma. Granitoids and high-pressure metamorphic rocks range from 78 to 53 Ma. Paleontology constraint on the Devils Racecourse Formation provides the oldest age of 120 Ma. Jamaica retroarc rocks give a mean of 65 ± 29 Ma (2σ).

3.3. Immobile Trace Element Geochemistry of the GAA

We used immobile trace element plots to determine original lithologies because these are less susceptible to alteration and better allow identification of petrogenetic and geodynamic attributes of GAA igneous rocks. First, the 1,112 screened igneous origin rocks are classified on the basis of incompatible element ratios Zr/Ti versus Nb/Y (Figure 10a). Most data (91%) plot in low Nb/Y sub-alkaline fields: basalt (49%), andesite/basaltic andesite (34%), and rhyolite/dacite (8%). Far fewer data plot in the high Nb/Y alkaline fields: alkali basalt (4%), trachy-andesite (5.6%), and trachyte (0.5%). Based on this classification, subalkaline basalts dominate the GAA, followed by andesite and basaltic andesite.

There is a noticeable geographic bias in the 1,112 samples, with 271 analyses from Cuba (52% of GAA area, 24% of data), 214 analyses from Hispaniola (38% of GAA area, 19% of data), 76 analyses from Jamaica (5.5% of GAA area, 6.9% of data), 480 analyses from Puerto Rico (4.5% of GAA area, 43% of data), and 71 analyses from Virgin Islands (0.1% of GAA area, 6.4% of data; Figure 11b). For plotting on tectonic discrimination diagrams, the 6 lithologies indicated above are further grouped into mafic and felsic rocks. Mafic refers to basalt, alkali basalt, and andesite/basaltic andesite (86% of data); and felsic refers to trachy-andesite, trachyte, and rhyolite/dacite (14% of data). By this measure, the GAA is overwhelmingly a mafic construction, as expected for intra-oceanic arcs (Stern, 2010).

3.3.1. Felsic Rocks: Ta-Yb Plot

GAA felsic rocks are found in all four tectonic settings: forearc ophiolite (Cuba), forearc melange (Cuba), magmatic arc (Hispaniola, Puerto Rico, Virgin Islands; Cuba Paleogene arc), and retro-arc (Jamaica). Most data fall into the volcanic arc granite (VAG) field on the Ta-Yb tectonic discriminant diagram (Pearce, Harris, & Tindle, 1984; Figure 12). A few samples plot in adjoining fields near VAG.

3.3.2. Mafic Rocks: Th/Yb-Nb/Yb Plot

This diagram (Figure 13) allows assessing the extent of subduction-related metasomatism and contamination by continental crust on the one hand versus magmas derived from mantle that was not affected by subduction, like

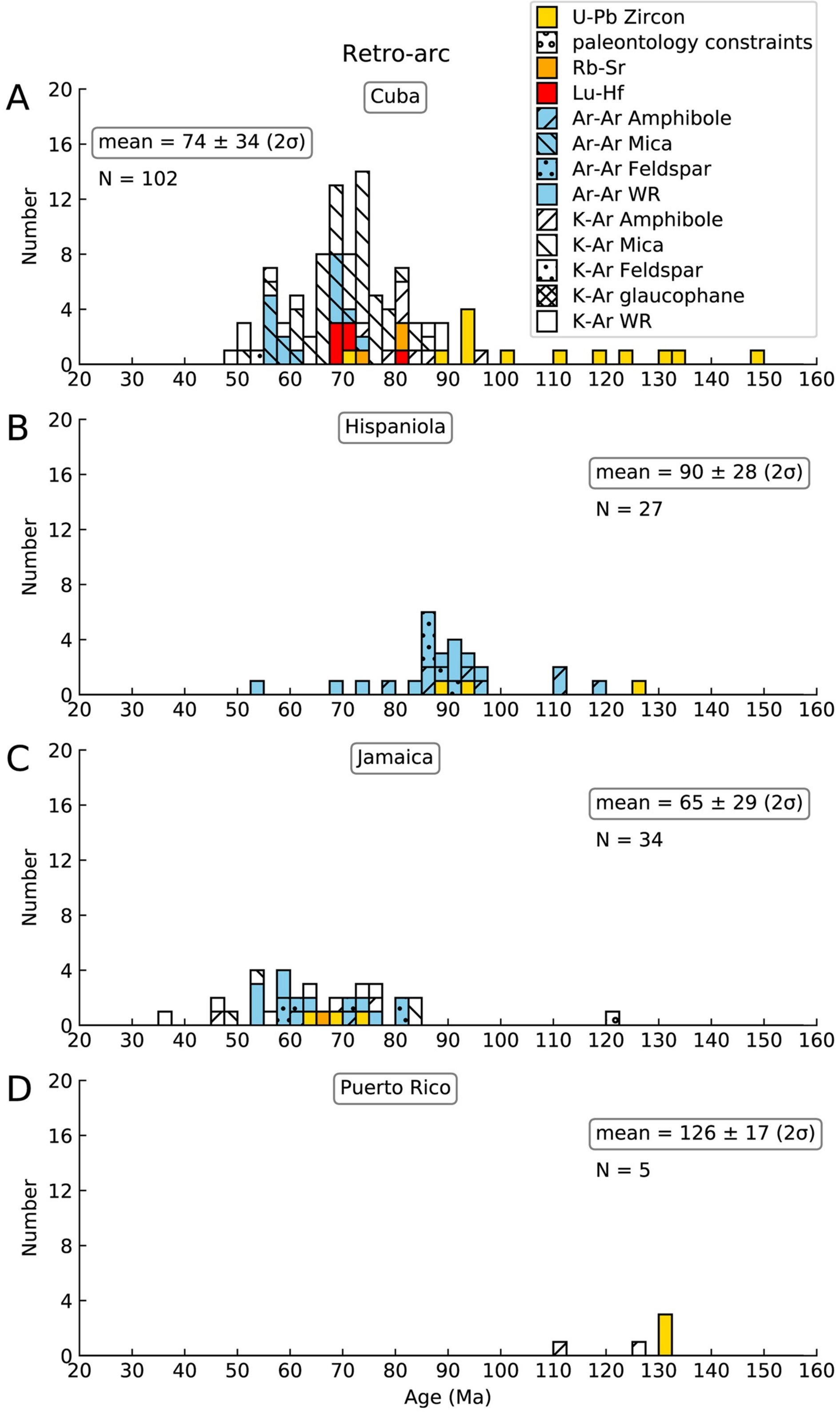

Figure 9. Histograms of compiled age data for the Greater Antilles Arc magmatic arc in (a) Cuba, (b) Hispaniola, (c) Jamaica, and (d) Puerto Rico.

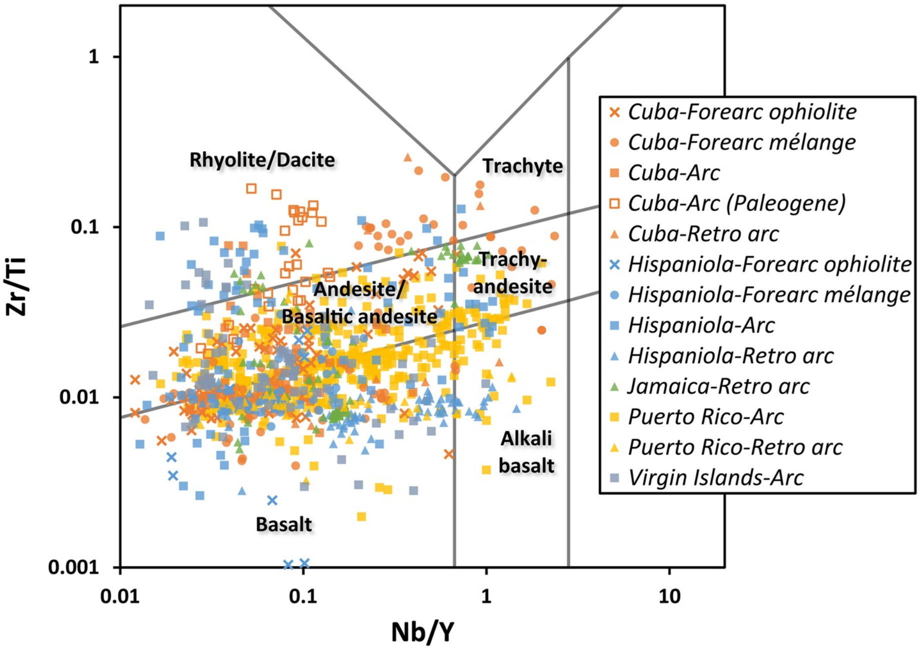

Figure 10. Zr/Ti versus Nb/Y diagram (after Pearce, 1996) for Greater Antilles Arc igneous rocks.

mid-ocean ridge basalts (MORB), enriched mid-ocean ridge basalts (E-MORB), and ocean island basalts (OIB; Pearce, 2008). Th and Nb are both more incompatible than Yb so Th/Yb and Nb/Yb covary for unmodified mantle, with low Nb/Yb and Th/Yb for basalts from depleted unmodified mantle like N-MORB and high Nb/Yb and Th/Yb for basalts from enriched mantle like OIB. The covariation defines the N-MORB to OIB "unmodified mantle array." Basalts generated from mantle that has been affected by melts/fluids evolved from subducted sediments or that interacted with continental crust will plot above the unmodified mantle array. Because the GAA was built on oceanic crust and is not underlain by continental crust, the samples that plot above the mantle array crystallized from magmas that formed above a subduction zone, as expected.

GAA forearc ophiolites are plotted in Figure 13a. These mostly show elevated Th/Yb, consistent with formation at a convergent plate margin. The metasomatized mantle source involved N-MORB and E-MORB mantle for the few samples from Hispaniola, and the wider spectrum in Cuba indicate that these sources were metasomatized as well as (local) metasomatized OIB mantle source. Figure 13b shows that forearc mélange blocks in Cuba and

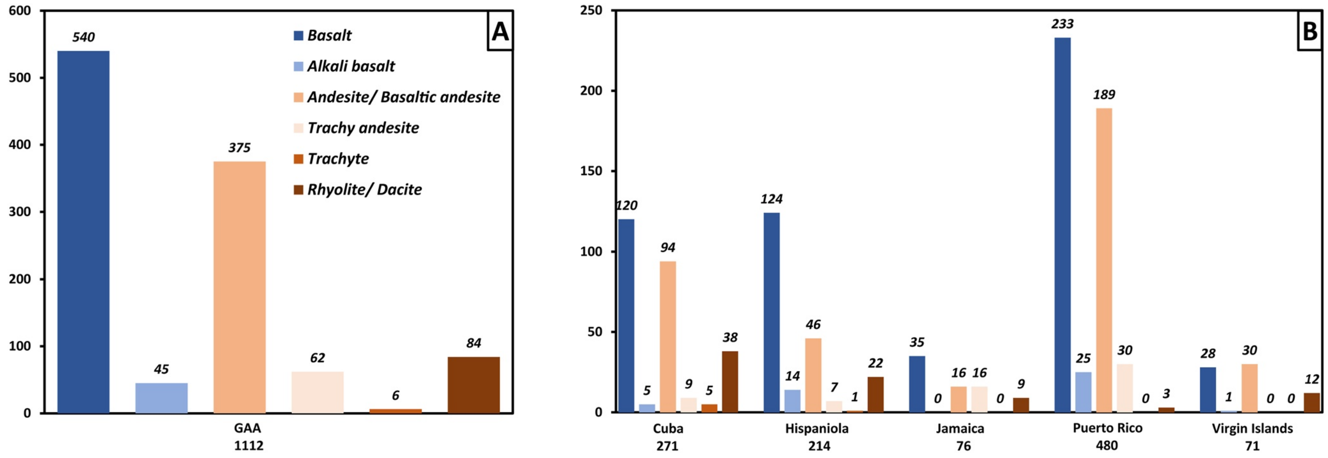

Figure 11. Histogram with lithologies from 1112 Greater Antilles Arc samples based on the Zr/Ti versus Nb/Y classification in Figure 10. (a) All samples and (b) individual islands.

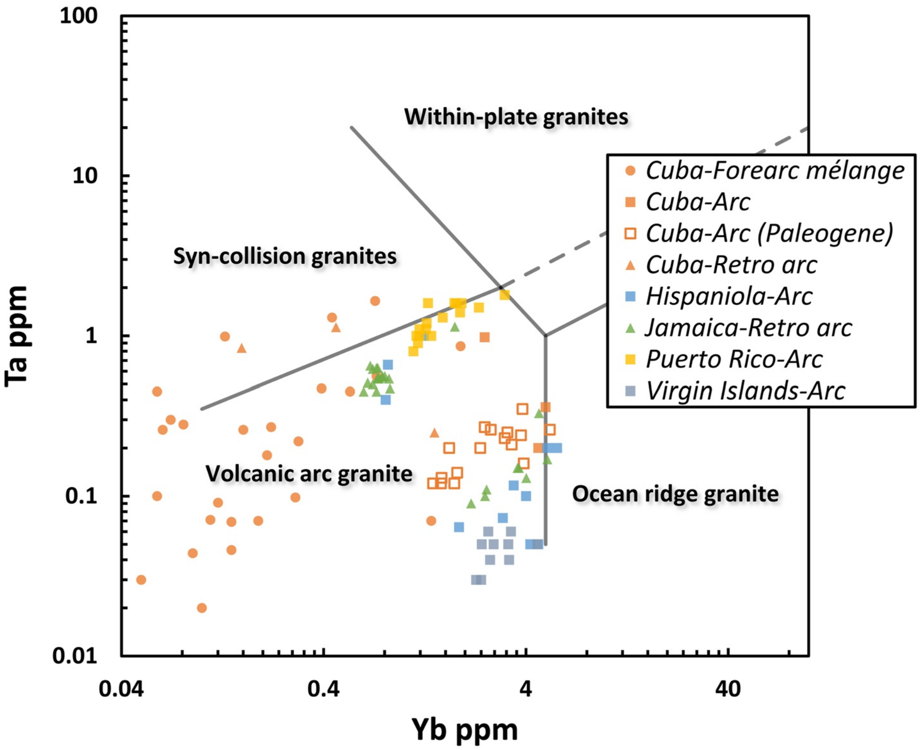

Figure 12. Felsic rocks (of trachy-andesite, trachyte and rhyolite/dacite composition) of the Greater Antilles Arc in the tectonic discrimination diagram of Pearce, Harris, and Tindle (1984). See text for further discussion.

Hispaniola exhibit a similar spectrum of mantle sources to those of forearc ophiolites, but Cuba data shows derivation from less metasomatized mantle sources compared to more metasomatized mantle sources suggested from Hispaniola data. Nearly all magmatic arc data show arc affinities, as expected. The magmatic arc of Hispaniola, Puerto Rico, and Virgin Islands present a wide spectrum of metasomatized mantle sources from N-MORB to OIB, in contrast to the Cretaceous and Paleogene magmatic arcs of Cuba, for which samples are more confined to metasomatized N-MORB to E-MORB (Figure 13c). Retro-arc samples show variable results, with Hispaniola-Cuba-Puerto Rico mostly plotting in the mantle array and Jamaica showing a clear arc affinity (Figure 13d).

3.3.3. Ti-V Plot

The Ti-V plot reveals variations in the behavior of V during partial melting and fractionation, which is thought to reflect magmatic oxygen fugacity. The basis of this plot is that Ti is always +4 and behaves as an incompatible element but V can be +3 or +4 in magmas and V^{+3} is more compatible than V^{+4}. Because convergent margin magmas are more oxidized than MORB or OIB, arc magmas have lower Ti/V. Arc magmas have Ti/V ratios equal to and less than 20, except for calc-alkaline magmas which show the effects of magnetite fractionation, therefore plotting magmatically evolved rocks should be done with caution. MORB and continental flood basalts have Ti/V ratios of about 20–50 and alkaline rocks have Ti/V generally >50. Back-arc basin basalts may have either arc-like or MORB-like Ti/V ratios.

Figure 14 shows that most mafic rocks of GAA fall into island arc tholeiite (IAT) and MORB/BABB fields. Most forearc ophiolite data show IAT and MORB/BABB affinity and some data from Cuba fall into the boninite field (Figure 14a). In Figure 14b, most forearc mélange data from Cuba fall into the MORB/BABB field, with fewer showing IAT affinity. The vast majority of magmatic arc data exhibit IAT and MORB/BABB affinity (Figure 14c), though there are also a few data showing boninite (Hispaniola) or OIB affinity. Most retro-arc data cluster in the IAT and MORB/BABB field and few rocks show OIB affinity (Figure 14d).

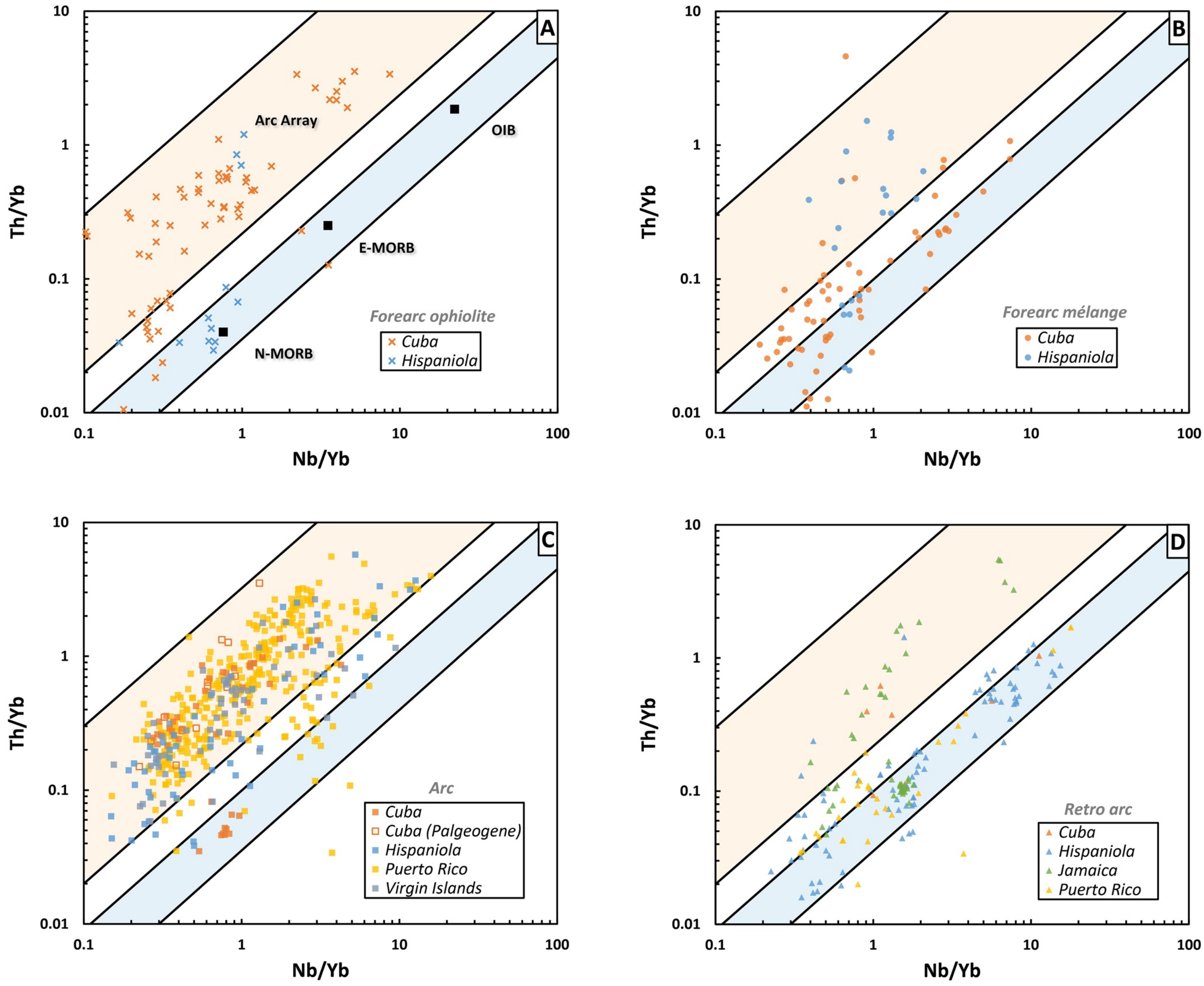

Figure 13. GAA mafic samples (of basalt, alkali basalt and andesite/basaltic andesite composition) plotted on the Th/Yb versus Nb/Yb of Pearce (2008). Light orange field indicates volcanic arc array and light blue field indicates mantle array. See text for further discussion.

3.3.4. Sr/Y Versus Y and La/Yb Versus Yb Plots

The Sr/Y versus Y and La/Yb versus Yb plots are typically used to discriminate adakite from normal arc andesitic, dacitic and rhyolitic magmas. The term adakite was coined by Defant and Drummond (1990) to describe intermediate to felsic, high Sr/Y and La/Yb volcanic and plutonic rocks produced by melting of the basaltic portion of oceanic crust in subduction zones. This requires unusual "hot" subduction and high-pressure evolution of magma where garnet is stable. In addition to slab melting (young and hot oceanic lithosphere and ridge subduction), high Sr/Y and La/Yb ratios can be produced by melting of mafic lower arc crust, fractional crystallization of hydrous mafic magmas, and high-pressure fractional crystallization of arc mafic magmas (Castillo, 2012; Moyen, 2009).

Figure 15 shows that most GAA intermediate to felsic rocks have high Y and Yb content and low Sr/Y and La/Yb ratios, falling into the normal island arc field. In Figure 15a, a few samples from forearc ophiolite, forearc mélange and retro-arc of Cuba and the volcanic arc of Hispaniola, Puerto Rico and Virgin Islands fall into the high Sr/Y adakite field. In Figure 15b, a few samples from forearc mélange and retro-arc of Cuba, volcanic arc of Hispaniola, Puerto Rico and retro-arc of Jamaica fall into the high Sr/Y and La/Yb adakite field.

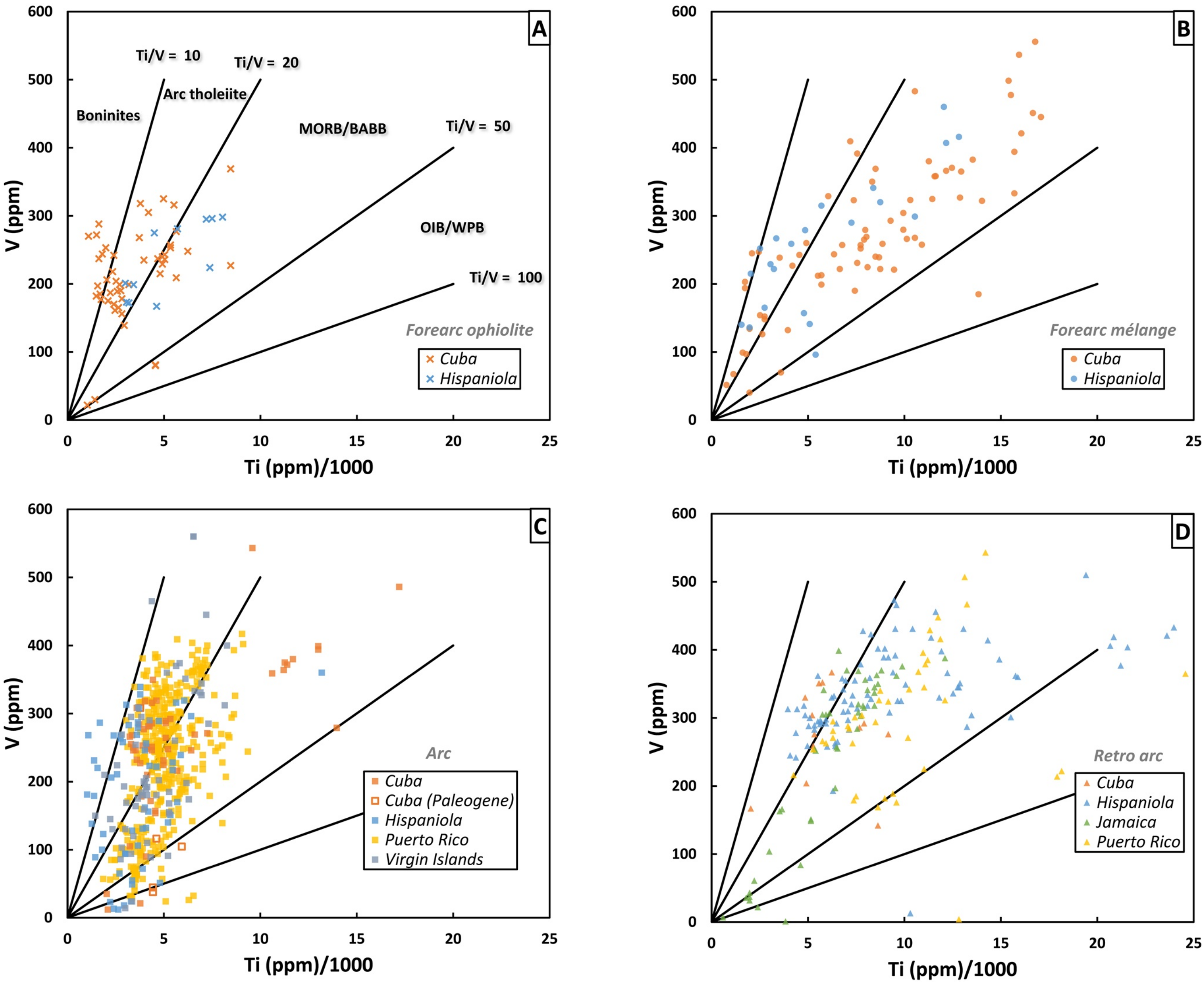

Figure 14. Ti/1,000 (ppm) versus V (ppm) diagram from Shervais (1982) for Greater Antilles Arc mafic rocks (basalt, alkali basalt, and andesite/basaltic andesite). See text for further discussion.

4. Discussion

Below we discuss five aspects of our compilation. First, we discuss the extent to which our compiled data are biased. Second, we discuss the extent to which a SI model can be usefully applied to the system. Third, we discuss the extent to which the CLIP affected the GAA. Fourth, we discuss some complications and considerations. Finally, we offer some suggestions for future research.

4.1. What Are the Biases in the Data and Assumptions in Our Approach?

We are aware of four significant biases in our compilation: technique, geologic, geographic, and land/sea. Technique bias reflects the fact that some radiometric methods (e.g., U-Pb zircon, ^{40}Ar-^{39}Ar) are more reliable than others (e.g., K-Ar). Geologic bias refers to the fact that ages pertain to either igneous or metamorphic episodes. Geographic bias refers to the fact that some islands have more geochronologic and geochemical data per unit area than others. Land/sea bias reflects the fact that nearly all the data in our compilation comes from subaerial exposures and we know little about the submerged GAA.

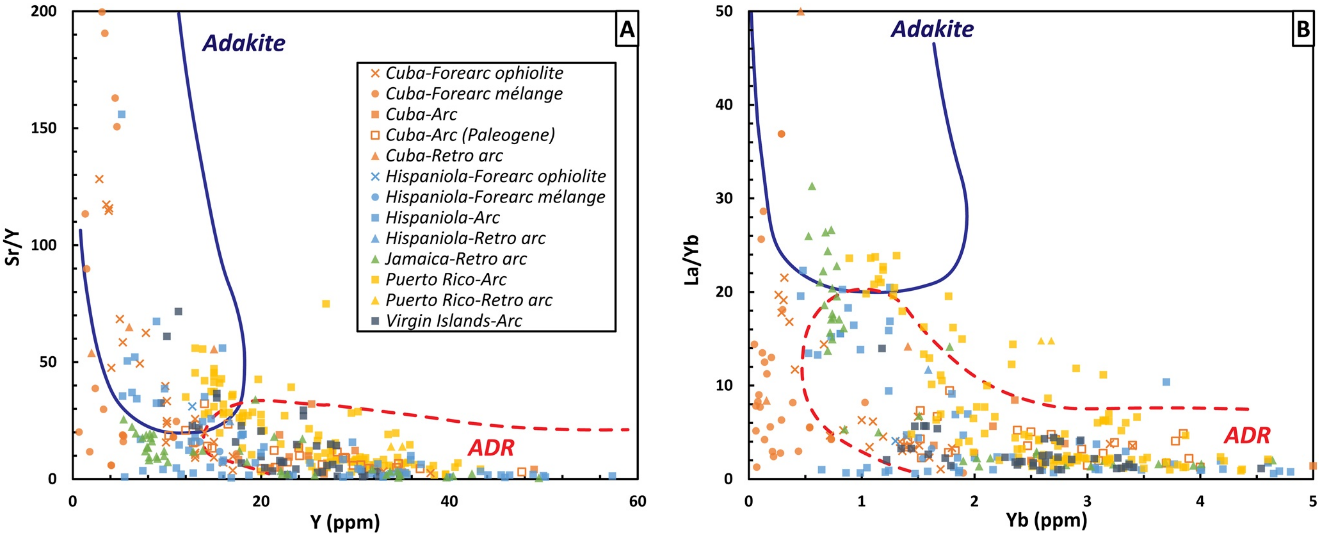

Figure 15. Plots of (a) Sr/Y versus Y and (b) La/Yb versus Yb after Castillo (2012) discriminating between adakitic and island-arc andesite, dacite and rhyolite (ADR) lavas for Greater Antilles Arc rocks with silica content greater than 56 wt%. See text for further discussion.

4.1.1. Technique Bias

Technique bias is a significant consideration for the geochronology compilation. A total of 662 radiometric ages and two paleontology constraints from the literature were compiled for Cuba, Hispaniola, Jamaica, Puerto Rico, and Virgin Islands, as shown in Figure 5. These studies used a wide range of radiometric techniques, with U-Pb zircon (21% of ages) and ^{40}Ar-^{39}Ar (25% of ages) being the preferred techniques and K-Ar (50% of ages) considered least reliable. Ages determined by four other techniques (Rb-Sr, Re-Os, Lu-Hf, and paleontology) make up 4% of the age compilation and contribute little to technique bias. Ages by the three major techniques are distributed differently among the islands. Cuba accounts for about half (46.7%) of the 310 ages we compiled, 55% of which (169) are K-Ar ages. Hispaniola has 192 ages (29%), only 24% (46) of which are K-Ar ages. Jamaica has 5% of the data (34), 38% of which are K-Ar ages. Puerto Rico has 13% of the age data in our compilation, 80% of which are K-Ar ages. The Virgin Islands have 6% of the age data (40), 75% of which are K-Ar ages. We conclude that there is significant technique bias in the geochronology compilation.

Future geochronologic research will surely emphasize U-Pb zircon and ^{40}Ar-^{39}Ar techniques and promise to reduce technique bias. It is noteworthy that some modern thermochronologic techniques (e.g., monazite, titanite, and xenotime U-Pb) have not yet been conducted on GAA rocks. Fission track work on Cretaceous and Paleogene volcanic arc rocks in southeastern Cuba (Rojas-Agramonte et al., 2006) and Jamaica (Comer et al., 1980) reveals GAA exhumation history, and recent zircon and apatite (U-Th)/He ages on volcanic rocks in Jamaica (Cochran et al., 2017) and Puerto Rico (Román et al., 2021) provide further constraints on the kinematics of GAA collision and uplift.

4.1.2. Geologic Bias

Ages determined by radiometric techniques can be subdivided into those that date when a magma crystallized (crystallization age) or when a metamorphic rock cooled below a closure temperature (metamorphic age). A systematic difference in age is seen for some techniques in Figure 5a. For example, U-Pb zircon ages display an older mean of 92 Ma compared to younger mean ages from ^{40}Ar-^{39}Ar (74 Ma) and K-Ar (70 Ma) systems. These results indicate that ^{40}Ar-^{39}Ar and K-Ar ages are strongly influenced by resetting and/or represent cooling below ca. 400°C rather than the igneous/metamorphic formation age of the rock bodies. Four-hundred seventy nine ages are igneous crystallization ages and 183 are metamorphic/cooling ages. Igneous activity is better approximated with U-Pb zircon ages whereas metamorphic evolution and cooling/decompression rates are better approximated by ^{40}Ar-^{39}Ar dating of amphiboles and micas. This may account for the significant difference between mean U-Pb zircon age (92 Ma) and younger mean age from ^{40}Ar-^{39}Ar (74 Ma). Figure 5b distinguishes ages determined for igneous versus metamorphic rocks, but no significant difference in age is observed; igneous ages show a mean of 76 ± 48 Ma whereas metamorphic ages show a mean of 77 ± 43 Ma.

4.1.3. Geographic Bias

Geographic bias refers to whether a region is sampled in proportion to its exposures or not. One way to do this is to compare data density on a island basis, using the area of basement exposed on each island. Cuba has ~58% of exposed GAA basement, Hispaniola has ~30%, Jamaica has 2.3%, Puerto Rico has ~9.3%, and the Virgin Islands have ~0.7% (estimated basement, non-sedimentary outcrop, exposure areas calculated from Iturralde-Vinent et al. [2016], Escuder Viruete, Perez-Estaún, et al. [2007], Mitchell [2020], Lidiak and Anderson [2015], and Wilson et al. [2019]). These are the proportions expected for geographically unbiased data. Relative to this expectation, for geochronology Cuba is slightly undersampled with 46.7% of ages, Hispaniola is proportionally sampled (29% of ages) whereas Jamaica (5% of ages), Puerto Rico (13% of ages), and Virgin Islands (6% of ages) are oversampled (Figure 11b). Within Hispaniola, Haiti is undersampled (31% of basement exposures, 14.1% of the ages) relative to the Dominican Republic (69% of basement, 85.9% of the ages). Geographic bias is more pronounced in 1,112 samples with geochemical data. Cuba is undersampled with 271 analyses (58% of GAA area, 24% of plotted data) as is Hispaniola with 214 analyses (30% of GAA area, 19% of plotted data). Within Hispaniola, nearly all data come from the Dominican Republic (99.4%). Jamaica is oversampled with 76 analyses (2.3% of GAA area, 6.9% of data), Puerto Rico is strongly oversampled with 480 analyses (9.3% of GAA area, 43% of data), as are the Virgin Islands with 71 analyses (0.7% of GAA area, 6.4% of data; Figure 11b).

It should be noted that there is also geographic bias within countries. For example, in Hispaniola, there are significantly more samples for geochronology in the Central Cordillera than in the rest of the island.

4.1.4. Land/Sea Bias

This bias deals with the fact that GAA samples in our compilation mostly come from the islands and few data come from offshore. This is a particular problem for the forearc ophiolite and mélange and retro-arc, for which samples mostly come from the western collided half of the GAA. In the east, where slow oblique convergence continues, forearc ophiolite and mélange that are the eastern equivalents of their western counterparts are submerged, requiring marine geoscientific techniques to study. Some studies have been conducted in the submerged eastern forearc. Marbles and other metasediments dredged from ca. 400 km along the southern wall of the Puerto Rico Trench are reported derived primarily from island-arc and pelagic component, and some magnesian schists and serpentinites are found in the accretionary prism (Heezen et al., 1985; Perfit et al., 1980b). Forearc ophiolite and mélange also include possible submerged fragments of the North Slope terrane of northern Puerto Rico (Larue & Ryan, 1998). More studies also need to be conducted in the submerged Beata Ridge to the south of Hispaniola (Dürkefälden et al., 2019). The ridge has been classified as part of the Mesozoic CLIP (Hoernle et al., 2004).

4.1.5. Subduction Initiation in the Greater Antilles Arc

Investigating SI is the key to understanding the tectonic evolution of a convergent margin. It is increasingly recognized that suprasubduction zone ophiolites (Pearce, Lippard, & Roberts, 1984), metamorphic soles (Agard et al., 2007; van Hinsbergen et al., 2015), and sometimes boninites are generated during SI (Stern & Gerya, 2018), creating the fore-arc (Stern et al., 2012). Within the GAA, a long ophiolite belt parallels the western section of the magmatic arc in Cuba, offering an opportunity to study how this convergent plate margin and underlying subduction zone formed. Equivalent forearc units presumably exist offshore north of the eastern GAA, providing an attractive target for 21st century research.

Petrological and geochemical studies of ophiolitic crustal sequences mixed with volcanic arc units show both mid-ocean ridge basalt (MORB) and IAT signatures in the central (Andó et al., 1996) and the eastern parts (Marchesi et al., 2007; Proenza et al., 2006) of Cuba. Although the vertical relationships are unclear, such basalts are expected in a SI environment (Whattam & Stern, 2011). Boninite is also characteristic of some SI ophiolites and is found in the Havana ophiolite of Cuba (Fonseca et al., 1989; Kerr et al., 1999) and Puerto Plata ophiolitic complex, Cacheal complex (Escuder-Viruete et al., 2014), and Los Ranchos (Escuder-Viruete, Diaz de Neira, et al., 2006), Maimón (Torró, Garcia-Casco, et al., 2016; Torró, Proenza, Marchesi, et al., 2017; Torró, Proenza-Fernández, et al., 2016), and Amina (Escuder-Viruete, Contreras, Joubert, et al., 2007) Formations in Hispaniola. Also, Late Cretaceous volcanic rocks from Los Pasos Formation in Cuba (Torró, Proenza-Fernández, et al., 2016) and Cuaba subcomplex in Rio San Juan metamorphic complex (Escuder-Viruete & Castillo-Carrión, 2016) exhibit boninitic, low-Ti island arc tholeiitic, and normal tholeiitic signatures. However, Late Cretaceous Téneme Formation lavas in eastern Cuba show similar low-Ti IAT signatures with boninitic affinity suggesting later additions to the convergent margin (Proenza et al., 2006).

Spinels in ophiolitic peridotites are used to infer tectonic settings, with the highest Cr# spinels (Cr# = (Cr/Cr + Al)) associated with forearcs (Bonatti & Michael, 1989). SI-related forearc peridotite spinels vary widely (Morishita et al., 2011). Ophiolitic peridotite spinels from harzburgites in Havana-Matanzas ophiolites vary in Cr# from 0.21 to 0.73 (Llanes-Castro et al., 2018). A similar range of Cr# in ophiolitic peridotite spinels from eastern segment harzburgites varies from 0.36 to 0.72 (Gervilla et al., 2005; González-Jiménez et al., 2011; Marchesi et al., 2006; Proenza et al., 1999). Peridotites with coexisting high- and low Cr# spinels indicate variable melt compositions as expected for a magmatic system that produced both boninitic magmas (from ultra-depleted peridotites with high Cr# spinels) as well as tholeiitic melts (from less depleted peridotites with moderate Cr# spinels; Morishita et al., 2011). Alternatively, this may indicate a multi-episodic history of partial melting and/or refertilization processes.

Radiometric ages of ophiolites range from Early to Late Cretaceous (Figure 7a), with the oldest ophiolites in Cuba and Hispaniola giving similar ages (126 Ma; Escuder-Viruete et al., 2014; Escuder-Viruete, Friedman, et al., 2011; Lázaro et al., 2016; Rojas-Agramonte et al., 2016; Rui et al., 2020). Radiolarians in sediments that overly pillow basalt at Holguín provide biostratigraphic constraints that are between Hauterivian (132.9–129.4 Ma) and Barremian (129.4–125.0 Ma; Andó et al., 1996). Despite GAA fore-arc ophiolite ages showing a rather broad range, the oldest ages of forearc ophiolites together with active magmatic arc suggest SI in the Early Cretaceous beginning around 130 Ma (cf., Escuder-Viruete et al., 2014; Escuder-Viruete, Diaz de Neira, et al., 2006; Lázaro et al., 2016; Pindell et al., 2012; Rojas-Agramonte et al., 2011). To date, only one metamorphic sole has been identified in the Caribbean realm, and it has not been related to Early Cretaceous subduction inception. It is the Guira de Jauco amphibolite in eastern Cuba, with an ^{40}Ar-^{39}Ar cooling age of 77–81 Ma, that has been related to the emplacement of the Moa-Baracoa ophiolite during the Late Cretaceous (90–85 Ma) in a new subduction zone perhaps related to the effects of the Caribbean plume (Lázaro et al., 2013, 2015). Clearly, further work is needed to constrain the magmatic ages of GAA forearc ophiolites and formation ages of metamorphic soles.

4.1.6. Comparison to the S Tibet SI Example

The GAA SI sequence and evolution can be usefully compared to that of the convergent margin of southern Tibet, showing significant similarities and differences. The southern margin of Tibet is an excellent place to study SI because the rocks are well-exposed, forearc ophiolite and metamorphic sole ages cluster tightly (as expected from the SI hypothesis) and younger elements of a mature convergent margin (such as magmatic arc and forearc basin) are also present. The significance of especially the differences between the ages of similar features in GAA and clear examples of SI like Tibet need to be understood in our efforts to test and further develop SI hypotheses. Figure 16 shows that they have similar spatial scales, both being about 2,000 km long. As Figure 16 shows, the two convergent systems both began in Early Cretaceous time, both experienced prolonged subduction (~70–80 million years), and both were sites of Eocene collision. However, S Tibet ophiolites are dominantly the same age whereas a wider range of ages is found for GAA ophiolites. S Tibet metamorphic soles are about the same age as most SI ophiolites (~120 Ma) whereas GAA ophiolitic soles are associated with younger events (Lázaro et al., 2013, 2015). S. Tibet experienced abundant igneous activity with collision whereas the GAA did not. These observations underscore the importance of further research into the age and nature of especially GAA SI sequences.

The wider range of ophiolite ages within the GAA might reflect continued fore-arc extension after SI began in the Early Cretaceous. The formation of Late Cretaceous metamorphic soles and low-Ti IAT volcanism in eastern Cuba is further evidence of a more complicated subduction history for GAA compared to S Tibet. This might be due to changing subduction regimes, the influence of the CLIP (94–83 Ma; Escuder-Viruete, Perez-Estaún, et al., 2011; Hauff, Hoernle, Tilton, et al., 2000; Sinton et al., 1998), along-strike extension, or a combination of these. Some of these tectonic complexities and the possible effect of the CLIP on the GAA are discussed in separate section below.

4.2. The Role of the Caribbean Large Igneous Province (CLIP)

In this section, we discuss the extent to which the CLIP might have affected the Cretaceous evolution of the GAA. The CLIP consists of thickened oceanic crust (up to 20 km) in the central (submarine) part of the Caribbean Plate (Mauffret & Leroy, 1997) and is also accreted/uplifted as subaerial flood basalt sequences exposed around the

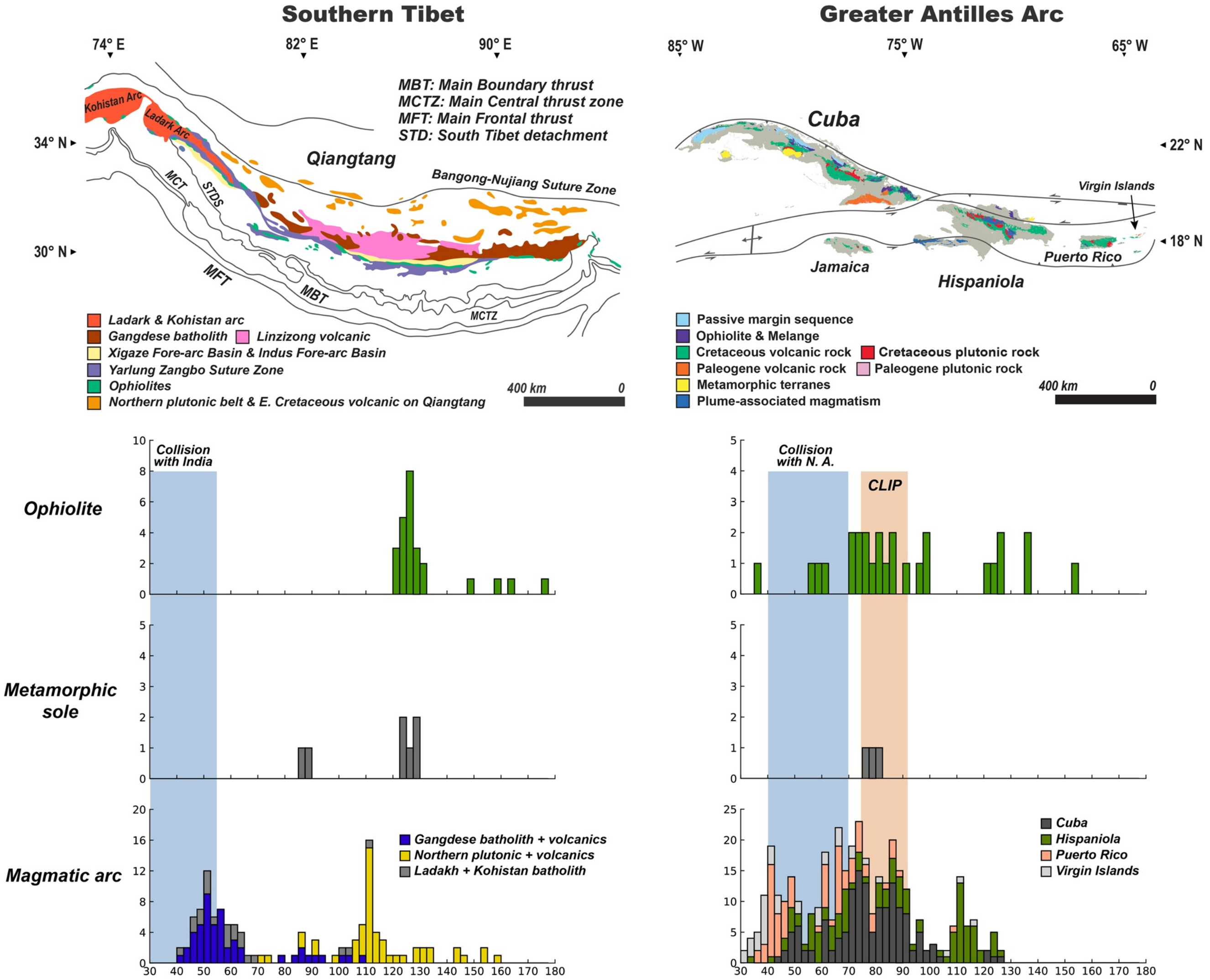

Figure 16. Comparison of two fossil convergent plate margins, at the same scale. Geochronologic data from ophiolite, metamorphic soles and magmatic arc of the Greater Antilles Arc (GAA) compared to the convergent system of southern Tibet (Hu & Stern, 2020). On the top left, simplified tectonic map of southern Tibet showing major ophiolitic massifs of the Yarlung Zangbo Suture Zone, Xigaze and Indus forearc basin and volcanic belts of the Lhasa terrane, modified after Hébert et al. (2012). On the top right, tectonic map of GAA from Figure 1a. First panel: histogram of compiled age data for ophiolites along the Yarlung Zangbo Suture Zone versus ophiolite of GAA. Second panel: histogram of compiled age data for metamorphic soles within the melange from Yarlung Zangbo Suture Zone versus GAA. Third panel: histogram of compiled age data of plutonic and associated volcanic rocks in the Lhasa terrane versus GAA. See text for further discussion.

margins of the Caribbean Sea and northwestern South America. Most authors favor an origin in the Pacific Ocean for the CLIP, possibly above the Galápagos mantle plume, and subsequent emplacement in the inter-America gap during the Cretaceous-Tertiary (e.g., Boschman et al., 2014; Duncan & Hargraves, 1984; Hastie & Kerr, 2010; Hoernle et al., 2002; Mann et al., 2007; Pindell et al., 2012; Sinton et al., 1997, 1998). Remnants of these terranes can be found in Central America, Colombia, Ecuador and in the Caribbean on Curaçao, Aruba, Hispaniola and Jamaica (e.g., Hastie et al., 2016; Hauff, Hoernle, Tilton, et al., 2000; Hauff, Hoernle, van den Bogaard, et al., 2000; Hoernle et al., 2004; Kerr et al., 1996; Loewen et al., 2013; Révillon et al., 2000; Sinton et al., 1998). New data from Dürkefälden et al. (2019) support long-term CLIP volcanism for at least 18 Ma, from ~92 to ~74 Ma with main magmatic activity from 89 to 90 Ma, though CLIP-related Duarte Complex lavas in the Dominican Republic date back to the Early Cretaceous (Escuder Viruete, Perez-Estaún, et al., 2007). Remnants of rocks with CLIP affinity in the GAA (Hispaniola, Jamaica, Puerto Rico, and offshore Hispaniola in the Beata Ridge) occur in a retro-arc position in our four-fold subdivision.

Recent papers, for example, by Dürkefälden et al. (2019) and Hastie, Ramsook, et al. (2010) still favor the idea of Duncan and Hargraves (1984) and Burke (1988) that collision between the ~90 Ma CLIP and the Great Arc of the Caribbean along an east-dipping subduction zone was responsible for a polarity reversal event during the Santonian-Campanian (~80–85 Ma; Burke, 1988), when a new west-dipping subduction zone was established. Recently, geochemistry of Cretaceous lavas from the Virgin Islands without a mantle plume component led Hastie et al. (2021) to conclude that the Caribbean subduction polarity reversal occurred in the Turonian-Campanian. However, the OIB-E-MORB source identified in the forearc, arc and retroarc (Figure 13) suggests the opposite. Furthermore, the geology and geochronology of Cuba, Hispaniola and Puerto Rico do not support the idea of a polarity reversal event at any stage of the Cretaceous arc-building process (Boschman et al., 2014; Braszus et al., 2021; Mann et al., 2007; Pindell et al., 2005, 2012; Rojas-Agramonte et al., 2011). Rather, the CLIP influence observed in other GAA islands suggests that varied degree of tectonic or geochemical interaction with the convergent margin was responsible for a significant amount of melting as well as metamorphism. For example, the CLIP shows tectonic influence on the Cuban segment of GAA, metamorphism of the Mabujina Amphibolite Complex (MAC) in central Cuba occurred during the Turonian (ca. 90–93 Ma) when it became part of the Cuban volcanic arc and was shortly after intruded by plutonic rocks of the Manicaragua batholith (Figure 8a; Turonian-Campanian; ca. 89–83 Ma; Rojas-Agramonte et al., 2011). Lázaro et al. (2013, 2015) postulated that the Late Cretaceous formation of the Güira de Jauco metamorphic sole (Figure 7a) and onset of obduction of the Moa-Baracoa ophiolite was triggered by the emplacement and development of the CLIP plume head. In Hispaniola, CLIP component has been identified in the geochemistry of igneous rocks of the supra-subduction zone environment (Escuder-Viruete et al., 2008). Farré-de-Pablo et al. (2020) conclude that chromitite from Loma Caribe peridotite formed by plume-derived melts that interacted with supra-subduction zone mantle in a Late Cretaceous back-arc setting in Hispaniola. The extent of interaction between CLIP and different segments of the GAA is still unclear, however, multiple lines of tectonic and geochemical interaction with the convergent margin of GAA and geochronology data displayed in Figure 16 suggests the emplacement of the CLIP during the Late Cretaceous imposes influence on the subduction zone magmatic, metamorphic and tectonic processes.

4.3. Other Complications and Considerations

We must keep in mind that our fourfold subdivision of units into mélange, forearc ophiolite, magmatic arc, and retro-arc may be flawed. For example, there may have been more than one subduction zone, as Jamaica rocks that fall into the retro-arc subdivision show an arc affinity (Figure 14d). Another complication may be that during the Early Cretaceous, a subducting proto-Caribbean ridge separated the North and South American plates (Blanco-Quintero, Gerya, et al., 2011; Blanco-Quintero, Lázaro, et al., 2011; García-Casco, Lázaro, et al., 2008; Pindell et al., 2005). This ridge may have been subducted beneath the eastern Cuban segment of the arc (trench-trench-ridge triple junction) in Early Cretaceous time (ca. 120 Ma; Blanco-Quintero et al., 2010), with the North American plate subducted beneath the Cuban arc and the South American plate subducted beneath the Hispaniola-Puerto Rico branch of the arc. The eastern migration of the triple point during the mid-Cretaceous in Hispaniola (Escuder-Viruete, Contreras, Stein, et al., 2007) could have resulted from the segmentation of proto-Caribbean ridge by transform faults (Rojas-Agramonte et al., 2021), causing Late Cretaceous adakitic magmatism in Hispaniola. The location of the triple junction during the Late Cretaceous is not known, but a shift toward the east (present coordinates) can be inferred if it was connected to the Central Atlantic ridge. Hence, with time, more and more North American plate was subducted below the GAA.

Also, Cenozoic normal and strike-slip faulting may have displaced geologic bodies from their original position to their present geographic position. We do not think that there has been major shuffling of original GAA tectonic units because the N. Caribbean transform fault system, with the largest displacements, trends sub-parallel to the GAA trend. However, large-scale thrusting may have had an effect in re-locating some tectonic units. This is, for example, the case of latest Cretaceous-Eocene orogenic thrust tectonics in western Cuba, where the oceanic arc-ophiolitic Bahía Honda-Cajálbana units now lie north of the North America passive margin sequences and can be restored 220 km to the south of its present position (e.g., Saura et al., 2008). On the other hand, metamorphic complexes made of sediments and igneous rocks in Cuba (Escambray complex and Pinos terrane) now located in the retro-arc originated in the North American passive margin and were metamorphosed beneath the Cretaceous forearc during subduction of Mesozoic passive margin sequences (Cruz-Gámez et al., 2016; Despaigne-Díaz et al., 2016, 2017; García-Casco, Iturralde-Vinent, & Pindell, 2008). Furthermore, serpentinite mélange units of the Escambray complex contain subducted oceanic crust (eclogites and blueschists) similarly formed in the Cretaceous forearc (García-Casco et al., 2006; Schneider et al., 2004).

Concerning ophiolites, the Cuban eastern ophiolite belt (Mayarí-Cristal and Moa-Baracoa) overthrusts volcanic arc exposures now located to the south. Hence, its classification as forearc ophiolite is controversial. In fact, most publications consider these ophiolitic rocks as formed in the Cretaceous back-arc (Iturralde-Vinent, 1998; Lázaro et al., 2013, 2015; Marchesi et al., 2006, 2007, 2011, 2016). However, Lázaro et al. (2016) identified fore-arc basaltic blocks within La Tinta mélange, which is associated to the Moa-Baracoa ophiolitic complex, while Rui et al. (2020) suggests that the Moa-Baracoa harzburgites originated in a nascent forearc mantle.

In Hispaniola, the Loma Caribe peridotite, the largest ophiolitic complex of the Dominican Republic, formed in an intra-arc/back-arc basin, in line with its present position, but the peridotite belts of southwestern Puerto Rico, now present in the retro-arc, may have formed in different Cretaceous tectonic positions, including the Farallon plate (Pacific-derived) in the retro-arc and the incoming Proto-Caribbean lithosphere (Atlantic-derived; Escuder-Viruete et al., 2008, 2009; Farré-de-Pablo et al., 2020; Lewis et al., 2006; Lidiak et al., 2011; Montgomery et al., 1994; Proenza et al., 2007).

In the retro-arc region, there are Late Cretaceous-Paleocene volcanic arc rocks in the Cayman Ridge and Nicaraguan Rise. The Cayman Ridge has been interpreted variously including a remnant arc after the GAA split in two and formed the Yucatan Basin since the Maastrichtian (Perfit & Heezen, 1978; Rosencrantz, 1990). However, granitoids of intermediate composition recovered from the Cayman Ridge show distinct continental affinity (Kysar et al., 2009; Lewis et al., 2005), in contrast to island arc composition of the Sierra Maestra in southeastern Cuba (Rojas-Agramonte et al., 2004). Lewis et al. (2011) indicated that granitoids recovered from the Nicaraguan Rise fall in the high-K calc-alkaline field of GAA granitoids, similar to those intrusions in Jamaica and Haiti, which they suggest formed in response to another northward subduction system.

4.4. Suggestions for Future Research

Our compilation indicates that there is much more work to be done before we have a full understanding of how the GAA intraoceanic arc system formed and evolved. The geographic bias we document indicates that geochemical and geochronological research in Cuba and Haiti needs to increase significantly. Large geologic systems that cross political boundaries require special efforts compared to those within a single political entity. In this situation, co-ordination between geologists in the entities is called for, for example, reinforcing the Caribbean Geological Conference and the Caribbean Journal of Earth Science (http://www.caribjes.com/) and other local journals and, perhaps, the formation of a Greater Antilles Geological Society. Such efforts would also stimulate research co-operation between geoscientists of GAA nations and territories and attract international researchers.

Another opportunity exists to apply modern thermochronologic techniques (e.g., U-Th-He, monazite, titanite, and xenotime U-Pb), that should be carried out to decipher uplift history across and along the GAA, especially its relationship to collision with Maya Block and the Bahamas Platform.

Another opportunity is to exploring how a trench with active convergence changes along strike into a suture zone. Oblique convergence continues in the east (Mann et al., 2002) and an active subduction zone can be traced by deep seismicity as far west as western Dominican Republic (Hayes, 2018). GAA along with the Izu collision zone of Japan and the Makran-Zagros transition in Iran are the only places in the world where a trench with active subduction can be traced along strike into a suture zone. Such transitions warrants further investigation so we can better understand what happens when a subduction zone becomes a collision zone.

Because so much of the GAA is above sea-level, we can build on what we know from studying exposed arc crust and mantle and extend this offshore, especially to the N into the forearc and S into the retroarc and the CLIP. There is much we can learn about SI from studying the GAA forearc. We are beginning to make progress understanding the on-land forearc, represented by the long ophiolite belt that parallels and lies north of the west-central magmatic arc in Cuba, but we know nothing about equivalent forearc crust that must exist offshore north of the eastern GAA, where subduction continues. Marine geoscientific research to study the eastern GAA forearc is needed. Studies of retroarc crust should begin with studying steep exposures south of SE Cuba and the Aves Ridge, the natural continuation of the island arc to the east and south of the GAA. In this regard, the effects of subduction of the Proto-Caribbean ridge, separating North and South American plates and now totally consumed, should be considered in understanding the evolution of the volcanic arc.

5. Conclusions

The Greater Antilles islands of Cuba, Hispaniola, Puerto Rico, Jamaica, and the Virgin Islands are fragments of the GAA, an unusually well-preserved fossil intra-oceanic convergent margin. The GAA is the result of subduction of the North and South American plate beneath the Caribbean plate that lasted for ∼90 m.y. in the west and continues today in the east. The "soft" collision between GAA and Maya and Bahamas margins caused uplift and exposure of the western GAA, providing an excellent natural laboratory for studying the formation and evolution of an intra-oceanic convergent margin. We compiled 664 (mostly) radiometric ages and more than 1,500 geochemical analyses for GAA igneous and metamorphic rocks and assigned these to a simple fourfold subdivision of the GAA based on relative geographic position to the magmatic arc: fore-arc mélange, fore-arc ophiolite, magmatic arc, and retro-arc and use these data to inspect the evolution of the GAA, from SI through maturity and demise. The oldest ages of forearc ophiolites together with those of the magmatic arc suggest subduction began in Early Cretaceous time at around 130 Ma. The geochronological data suggest that the GAA was, at least partially, strongly affected by the CLIP in Late Cretaceous time (e.g., MAC, Central Cuba; Güira de Jauco metamorphic sole, Eastern Cuba; Loma Caribe peridotite). Some peaks are seen in the histograms, especially in the Late Cretaceous from 95 to 60 Ma, that may relate to the CLIP event(s) and with events of collision with passive margins. Two subordinate peaks are observed at 120–110 Ma and ∼40 Ma. Immobile trace element geochemical data show that the GAA is dominated by mafic igneous rocks, as expected for an intraoceanic convergent margin. The arc shows trace element concentrations expected for convergent margin magmas and these trace element concentrations for retroarc igneous rocks in central and southern Hispaniola are more like OIB and MORB. In spite of multiple biases, the database presented here is a useful step forward in the effort to help overcome some of the obstacles and motivate systematic study of the GAA. Our results encourage forming of regional partnerships, involvement of international partners, and exploration of offshore regions.

Data Availability Statement

Data sets for geochronologic compilation of this research are available through the following references (and its Supporting Information S1 files): Abbott et al. (2016), Alminas et al. (1994), Barabas (1982), Bellon, Mecier de Lepinay, and Vila (1985), Bellon, Vila, and Mercier de Lepinay (1985), Blanco-Quintero, Rojas-Agramonte, et al. (2011), Bowin (1975), Cárdenas-Párraga et al. (2012), Castro et al. (2019), Cheilletz et al. (1978), Chubb and Burke (1963), Cochran et al. (2017), Cox et al. (1977), Despaigne-Díaz et al. (2016), Donnelly (1966), Draper and Nagle (1991), Escuder-Viruete (2010), Escuder-Viruete, Diaz de Neira, et al. (2006), Escuder-Viruete, Contreras, et al. (2006), Escuder Viruete, Perez-Estaún, et al. (2007), Escuder-Viruete, Contreras, Stein, et al. (2007), Escuder-Viruete et al. (2008), Escuder-Viruete et al. (2010), Escuder-Viruete, Perez-Estaún, Gabites, and Suarez-Rodriguez (2011), Escuder-Viruete, Friedman, et al. (2011), Escuder-Viruete, Perez-Estaún, et al. (2011), Escuder-Viruete, Valverde-Vaquero, Rojas-Agramonte, Gabites, Carrion Castillo, et al. (2013), Escuder-Viruete, Valverde-Vaquero, Rojas-Agramonte, Gabites, and Pérez-Estaún (2013), Escuder-Viruete, Joubert, et al. (2016), Escuder-Viruete, Suárez-Rodríguez, et al. (2016), García-Casco et al. (2001), García-Casco et al. (2002), García-Casco et al. (2003), Grafe (2000), Grafe et al. (2001), Hall et al. (2004), Hastie (2007), Hastie et al. (2009), Hastie, Kerr, et al. (2010), Hastie, Ramsook, et al. (2010), Hastie et al. (2013), Hatten et al. (1988), Hertwig et al. (2016), Hernaiz Huerta et al. (2012), Iturralde-Vinent et al. (1996), Japan International Cooperation Agency (1985), Jolly and Lidiak (2006), Joyce and Aronson (1987), Kesler (1971), Kesler and Sutter (1979), Kesler et al. (1977), Kesler et al. (1991), Kesler et al. (2004), Kesler, Campbell, and Allen (2005), Kesler, Campbell, Smith, et al. (2005), Khudoley (1967), Kirk et al. (2014), Krebs et al. (2008), Kysar et al. (1998), Lapierre et al. (1999), Laverov et al. (1967), Lázaro et al. (2009), Lázaro et al. (2015), Lázaro et al. (2016), Lewis et al. (1973), Loewen et al. (2013), Monthel (2010), Mueller et al. (2008), Nelson et al. (2015), Odin et al. (2001), Pérez (2008), Perfit et al. (1980a), Proenza et al. (2006), Rankin (2002), Rojas-Agramonte et al. (2004), Rojas-Agramonte et al. (2006), Rojas-Agramonte et al. (2010), Rojas-Agramonte et al. (2011), Rojas-Agramonte et al. (2016), Rojas-Agramonte et al. (2021), Rui et al. (2020), Schneider et al. (2004), Schrecengost (2010), Sinton et al. (1998), Speed et al. (1979), Stanek et al. (2019), Torró, Camprubí, et al. (2017), Torró, Proenza, Camprubí, et al. (2017), Torró et al. (2018), Vila et al. (1986), Wadge et al. (1982), and West et al. (2014). Data sets for geochemical compilation of this research are available through the following references (and its Supporting Information S1 files): Abbott et al. (2016), Blanco-Quintero et al. (2010), Blanco-Quintero, Lázaro, et al. (2011), Castro et al. (2019), Cazañas et al. (1998), Cruz-Gámez et al. (2016), Escuder-Viruete, Diaz de Neira, et al. (2006), Escuder Viruete, Perez-Estaún, et al. (2007), Escuder-Viruete, Contreras, Stein, et al. (2007), Escuder-Viruete et al. (2008), Escuder-Viruete et al. (2009), Escuder-Viruete et al. (2010), Escuder-Viruete, Friedman, et al. (2011), Escuder-Viruete, Perez-Estaún, et al. (2011), Escuder-Viruete et al. (2014), Escuder-Viruete, Joubert, et al. (2016), Escuder-Viruete, Suárez-Rodríguez, et al. (2016), Cintron Franqui et al. (2017), Schellekens and Smith (1998), Hastie et al. (2007), Hastie et al. (2008), Hastie, Kerr, et al. (2010), Hastie et al. (2013), Jolly and Lidiak (2006), Jolly et al. (1998), Jolly et al. (2002), Jolly et al. (2008a), Jolly et al. (2008b), Kerr et al. (1999), Lázaro and García-Casco (2008), Lázaro et al. (2011), Lázaro et al. (2013), Lewis et al. (2011), Lidiak and Jolly (1998), Lidiak et al. (2011), Marchesi et al. (2006), Marchesi et al. (2007), Pérez (2008), Proenza et al. (2006), Rojas-Agramonte et al. (2004), Rojas-Agramonte et al. (2016), Rojas-Agramonte et al. (2021), Schellekens (1998a), Schellekens (1998b), Torró, Proenza, Marchesi, et al. (2017), Torró, Camprubí, et al. (2017), Torró et al. (2020), and West et al. (2014).

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