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The role of arc migration in the development of the Lesser Antilles: A new tectonic model for the Cenozoic evolution of the eastern Caribbean

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ABSTRACT

Continental arc systems often show evidence of large-scale migration both toward and away from the incoming plate. In oceanic arc systems, however, while slab roll-back and the associated processes of backarc spreading and arc migration toward the incoming plate are commonplace, arc migration away from the incoming plate is rarely observed. We present a new compilation of marine magnetic anomaly and seismic data in order to propose a new tectonic model for the eastern Caribbean region that includes arc migration in both directions. We synthesized new evidence to show two phases of backarc spreading and eastward arc migration toward the incoming Atlantic. A third and final phase of arc migration to the west subdivided the earlier backarc basin on either side of the present-day Lesser Antilles arc. This is the first example of regional multidirectional arc migration in an intra-oceanic setting, and it has implications for along-arc structural and geochemical variations. The back and forth arc migrations were probably due to the constraints imposed by the neighboring American plates on this isolated subduction system, rather than variations in subducting slab buoyancy.

INTRODUCTION

Arc migration is a common feature of oceanic subduction systems. When upper-plate extension results in backarc spreading, generally due to slab roll-back, arcs often split into extinct and active arc segments (Karig, 1974). This results in the movement of both the trench and active magmatic front toward the incoming plate. Arc migration in the opposite direction, however, is very unusual and rarely impacts the whole arc front (e.g., Yang et al., 1996). In contrast, in continent-ocean systems, arc migration in both directions is common. Migration away from the incoming plate of many hundreds of kilometers is often accompanied by (temporary) arc shutdown (e.g., Gerya et al., 2009). Such events are commonly attributed to the subduction of large buoyant features, such as extinct mid-ocean ridges or plateaus, which results in a flattening of the slab (Gerya et al., 2009; Martinod et al., 2013).

The eastern Caribbean is a complex region with a history of island-arc migration (Fig. 1). Three separate subduction systems have been active at different times, although the mechanisms that relate them are disputed. The oldest volcanic system is known as the Great Arc of the Caribbean (GAC). This Cretaceous–Paleocene arc, of which the Aves Ridge is the clearest remaining expression, is identified from remnants throughout the Dutch, Venezuelan, and Greater Antilles and became extinct at ca. 59 Ma (Neill et al., 2011). Arc magmatism from 40 Ma is found on the islands of the Limestone Caribbees along the northeastern Caribbean plate boundary. Despite a record of various early Paleocene to Eocene subduction-related rocks tracking migration eastward through the Greater Antilles toward the Virgin Islands (Cox et al., 1977; Jolly et al., 1998), convincing evidence for backarc spreading in the Grenada Basin (GB) to accompany this arc migration has yet to be found. Scarce regional seismic and well data mean that the geometry of any spreading, and the nature of the crust underlying the basin are highly debated (Bird et al., 1999). It has even been suggested that the GB is an extended forearc, leaving its role in arc migration in the Paleogene highly uncertain (Aitken et al., 2011). A further unknown is the location of the southern arc during this time. Speed et al. (1993) recognized the need for a source of volcanic sediment here during the Eocene and Oligocene, yet they found no magmatic evidence for an arc at the site of the southern modern Lesser Antilles.

The final arc migration occurred in the early Miocene, when the Limestone Caribbees became extinct and the 750-km-long modern Lesser Antilles Arc (LAA) was established to the west. It has been proposed that this event was triggered by the subduction of an oceanic ridge, causing the migration of the northern arc segment (McCann and Sykes, 1984). The southern portion of the LAA is assumed to have formed in its current location with no intermediate phase of arc magmatism between extinction of the GAC (ca. 59 Ma) and the initiation of LAA volcanism at ca. 25 Ma (Aitken et al., 2011; Bird et al., 1999).

In this study, we combined new magnetic (Fig. 2) and seismic (Fig. 3) data sets acquired in the GB in C.E. 2016–2017 with existing geophysical, geological, and geochronological data to test current models for the development of the

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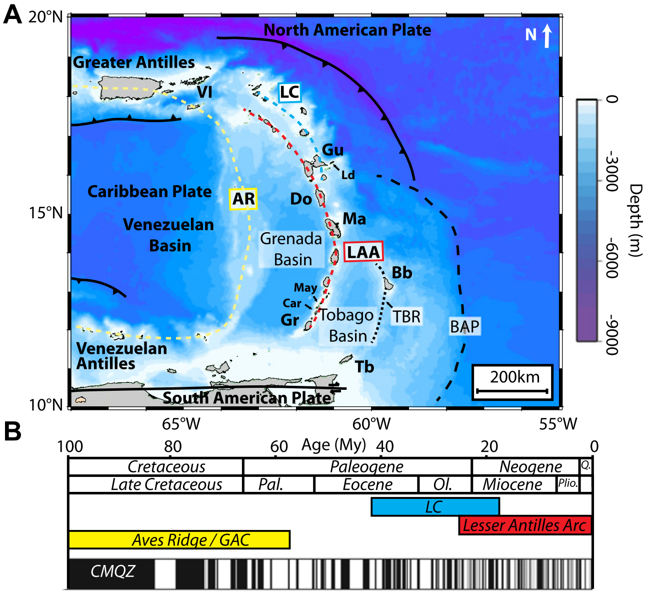

Figure 1. (A) Map of the Lesser Antilles region highlighting the major tectonic features. Abbreviations: LAA—Lesser Antilles arc (red dashed line), LC—Limestone Caribbees (blue dashed line), AR—Aves Ridge (yellow dashed line), VI—Virgin Islands, BAP—Barbados accretionary prism, TBR—Tobago-Barbados Ridge. Individual islands: Gu—Guadeloupe, Ma—Martinique, Gr—Grenada, Bb—Barbados, Tb—Tobago, May—Mayreau, Car—Carriacou; Ld—La Désirade; Do—Dominica. (B) Temporal framework of arc magmatism in the eastern Caribbean. A full breakdown of tectono-magmatic affinities and geochronology is provided in the Data Repository (section 3 and Fig. DR8 [see footnote 1]). GAC—Great Arc of the Caribbean; LC—Limestone Caribbees; CMQZ—Cretaceous magnetic quiet zone. The geomagnetic polarity time scale is shown for reference (Cande and Kent, 1995). Q—Quaternary; Pal—Paleocene; Ol—Oligocene; Plio—Pliocene.

LAA. We propose a new model for the tectonic evolution of the region in which the Eocene magmatism (of which the Limestone Caribbees are the only clear expression) was present to the east of the entire length of the current arc. A Miocene westward migration, again along the entire arc front, then divided the previous backarc into the GB and Tobago Basin (TB). The model explains several of the disputed aspects of the region's development and is more consistent with current geodynamical models of subduction behavior. It has significant implications for our understanding of both the structural variations along the LAA and the geochemistry of its magmatic products. We consider it a unique example of a retreating and advancing magmatic front in an oceanic arc setting.

NEW MODEL FOR THE EVOLUTION OF THE LESSER ANTILLES

Figure 2A shows our new reduced-to-pole magnetic anomaly chart for the study area. It is a levelled compilation of over 320 scientific cruises from 1950 to 2017 (full processing details are provided in the GSA Data Repository[1]) and is a significant improvement on existing charts for the region (Ghosh et al., 1984). Two of these cruises, JC133 and JC149 on the RRS *James Cook*, conducted as part of the VoiLA (Volatile Recycling in the Lesser Antilles; http://www.voila.ac.uk) project, also acquired north-south–oriented multichannel seismic reflection and wide-angle refraction profiles in the GB (Fig. 3). Wide-angle profiles (see full processing details in the Data Repository) were modeled using the software RAYINVR (Zelt and Smith,

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[1] GSA Data Repository item 2019326, extended discussion regarding the processing methodology of magnetic and seismic data discussed in the paper, and a detailed breakdown of geochemical data and studies used to define the three stages of arc volcanism shown in Figure 1, is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

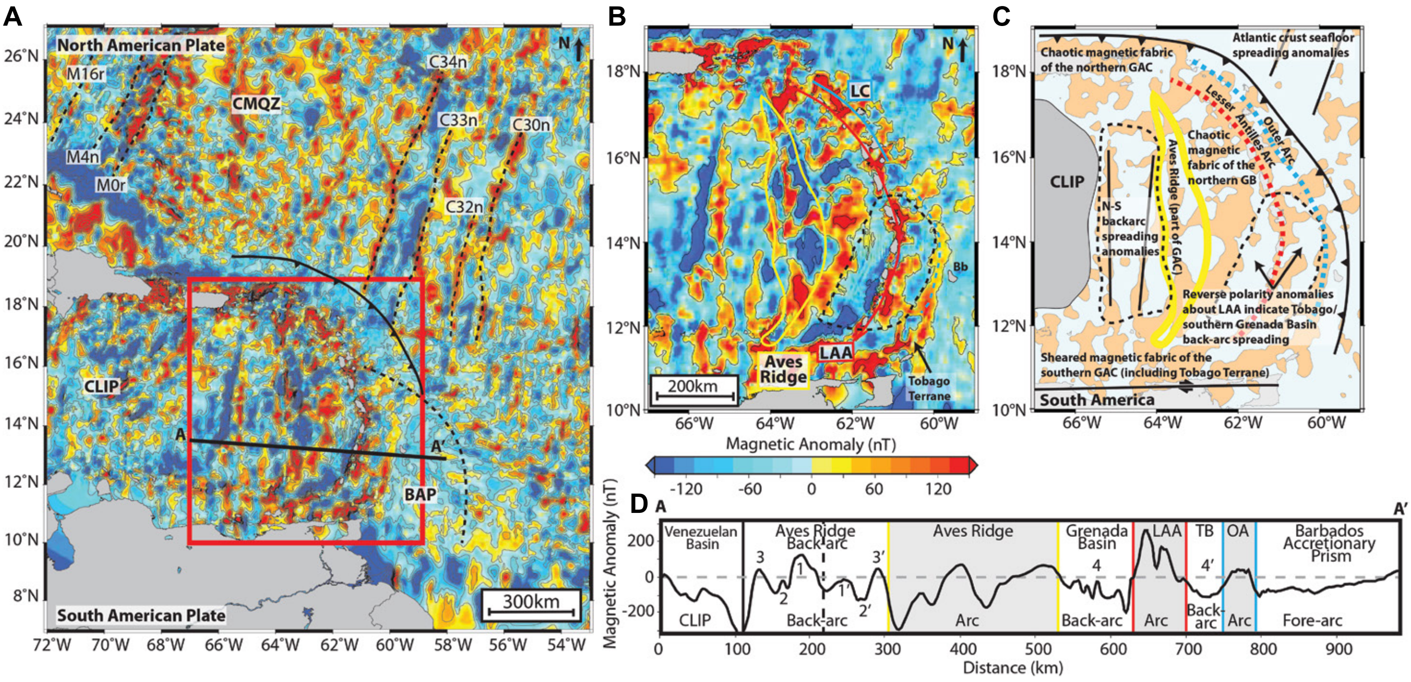

Figure 2. Magnetic and gravity data for the Caribbean region. (A) New regional magnetic anomaly grid. CLIP—Caribbean large igneous province; BAP—Barbados accretionary prism; CMQZ—Cretaceous magnetic quiet zone. (B) Detail of new magnetic anomaly grid over the Aves Ridge (outlined in yellow), Lesser Antilles arc (LAA, red line), and Outer arc (blue line marked with LC [Limestone Caribbees]). Black dashed line denotes potential extent of backarc spreading. Bb—Barbados. (C) Cartoon of key features in the anomaly grid over the LAA. Regions of normal magnetic anomaly polarity are shown in orange, with reverse in blue. (D) Cross section through magnetic grid along the profile shown in A. Magnetic highs are associated with Aves Ridge, LAA, and outer arc magmatism. Note symmetrical spreading anomalies in the Aves Ridge backarc and Grenada Basin (labeled 1–1′, etc.). GB—Grenada Basin; TB—Tobago Basin; OA—outer arc.

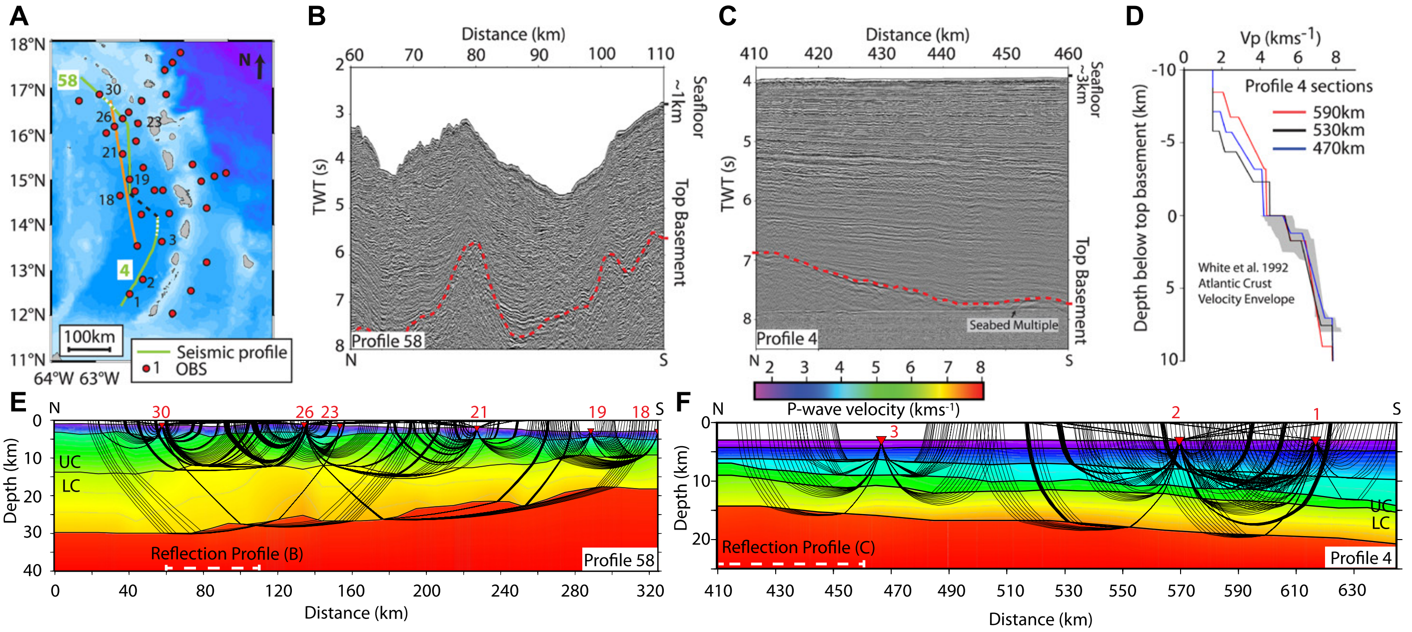

Figure 3. Crustal structure of Grenada Basin (GB). (A) Location of seismic reflection/refraction profiles (green) shot by the Volatile Recycling in the Lesser Antilles (VoiLA) project as part of RRS *James Cook* cruise JC149. Dashed white sections show subset of reflection profiles plotted in B and C. Orange profile gar1 is from the GARANTI 2017 experiment in the GB (R/V *L'Atalante*; Lebrun, 2017, personal commun.). Travel times from this experiment supplemented our own data set for wide-angle modeling at long offsets along profile 58. OBS—ocean-bottom seismometer. (B) Section of two-dimensional seismic profile 58 in the northern GB. (C) Section of two-dimensional seismic profile 4 in the southern GB. (D) One-dimensional velocity profiles at three points along refraction profile 4 (Fig. 3F), corrected to top basement and compared to the Atlantic crust oceanic velocity envelope from White et al. (1992). (E) P-wave velocity model for VoiLA project profile 58 in the northern GB; 1 in 10 of modeled rays are shown. UC—upper crust; LC—lower crust. (F) P-wave velocity model for VoiLA project profile 4 in the southern GB.

1992), and together these data sets allow us to offer new insights into the structure and evolution of this historically data-poor region.

The LAA is clear in our magnetic grid as a strong positive anomaly (Fig. 2). A parallel anomaly of similar character is visible to the east beneath the older Limestone Caribbees. However, rather than merging with the modern arc around Martinique, as in current tectonic models, it extends southward as an unbroken arc, buried beneath the thick sediment of the Barbados Accretionary Prism. This "outer-arc" magnetic anomaly passes ~15 km west of the island of Barbados and the so-called Tobago-Barbados Ridge (Fig. 1), both of which are thought to be uplifted sections of prism sediments (Gomez et al., 2018). Given its depth of burial (in excess of 10 km, making gravity modeling and seismic imaging of the basement crust difficult), it is the magnetic signature that makes it stand out. The outer-arc anomaly terminates against a similar positive anomaly of the Tobago terrane to the south (a Late Cretaceous GAC fragment trapped on the leading edge of the Caribbean plate; Boschman et al., 2014). We interpret the anomaly as evidence for the southward extension of Limestone Caribbees arc magmatism along the whole front of the eastern Caribbean plate boundary during the late Paleogene.

A region of dominantly reverse polarity is visible on either side of the LAA within the southern GB and TB, extending as far north as Dominica and Martinique (Fig. 2). This regional reverse polarity is consistent with slow backarc opening in the overriding plate during the dominantly reverse magnetic polarity chrons C26 to C18 (60–40 Ma; Fig. 1) as arc volcanism migrated from the Aves Ridge to its easternmost location during the Eocene. We propose that a final westward (away from the incoming plate) arc migration in the late Oligocene and establishment of the LAA divided the Paleogene backarc basin into the GB and TB. A common origin for these two basins has been proposed previously (Aitken et al., 2011). In our model, the geometry of these basins and their magnetic anomalies implies that the islands of the southern LAA now occupy the axis of the previous backarc spreading.

Backarc spreading in the southern GB and TB is supported by uplifted Paleocene–mid-Eocene submarine basalts and volcanogenic sediments on many of the southernmost islands of the LAA (e.g., the Mayreau Basalt and Anse Bandeau formation of Mayreau, ca. 50–46 Ma; Speed et al., 1993; see the Data Repository for further details). The chemical and isotopic compositions of these rocks are consistent with a depleted backarc source (Speed and Walker, 1991; White et al., 2017). Paleocene to mid-Eocene xenocrystic and detrital zircons found throughout the Grenadines possess a rare earth element composition that suggests they crystallized from magma produced from a much less oxidized mantle than the sources of the modern arc, again consistent with a backarc origin (Rojas-Agramonte et al., 2017).

Wide-angle seismic data (profile 4; Fig. 3F) further support our interpretation of backarc spreading in the southern GB. Here, thick (up to 11 km), flat-lying sediments overlie a structurally homogeneous 6–7-km-thick crust with a typical oceanic velocity structure (Fig. 3D). Oceanic crust was also interpreted by Christeson et al. (2008) in the far south of the basin and is likely to extend as far north as southern Martinique. Our new seismic reflection data show a smoothly undulating basement surface (Fig. 3), with no evidence for an east-west–striking spreading center as previously suggested (e.g., Pindell and Kennan, 2009).

In the northern GB, the crust thickens northward from 15 to ~27 km (Fig. 3E). Wide-angle modeling requires a high-velocity-gradient upper crust (4.5–6.6 km s^{-1}) and thick (>10 km) lower crust (6.8–7.2 km s^{-1}), similar to that observed beneath the arc by Kopp et al. (2011) near Guadeloupe. This crustal thickness rules out backarc spreading, and we interpret it as resulting from older arc magmatism in the overriding plate. Structural heterogeneities displayed in the rough seafloor/basement topography (Fig. 3B) and the chaotic magnetic fabric of the northern GB are the result of the complex tectonic history of the overriding plate and GAC magmatism. In contrast to the southern LAA, the islands of the northern LAA developed upon this older arc crust. Support for this comes from the island of La Désirade, where basement volcanic rocks give radiometric ages as old as the Late Jurassic (Neill et al., 2010).

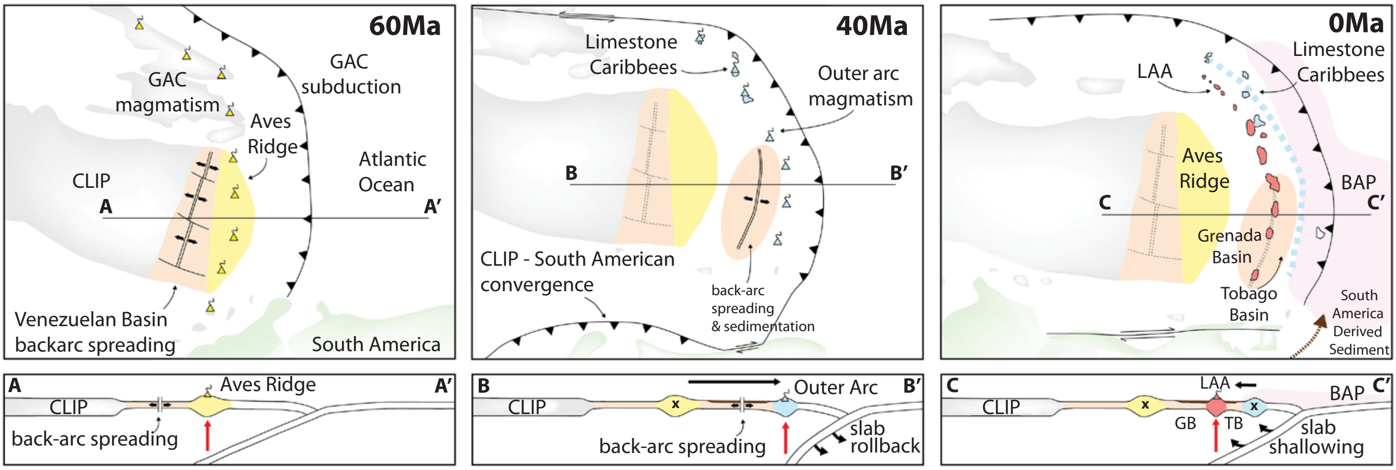

Figure 4. Cartoon of new tectonic model for the eastern Caribbean region. Locations of key tectonic blocks are based upon the reconstruction of Boschman et al. (2014). 60 Ma: Regional arc magmatism associated with the late stages of the Great Arc of the Caribbean (GAC). Evidence for this arc is found in the rock record of several island groups, including the Dutch, Venezuelan, and Greater Antilles, as well as in dredged samples from Aves Ridge. CLIP—Caribbean large igneous province. 40 Ma: Slab rollback has led to abandonment of the Aves Ridge and eastward migration of arc volcanism. New Outer arc includes the islands of the Limestone Caribbees to the north. Backarc spreading is limited to the south, with a north-south–oriented spreading axis. 0 Ma: Slab shallowing forces the abandonment of the Outer arc and establishment of the modern Lesser Antilles arc (LAA) to west. Arc volcanism has divided the former backarc basin into Tobago (TB) and Grenada (GB) Basins in the south. Direct evidence for southern extension of the Outer arc is buried beneath the Barbados accretionary prism (BAP).

The transition between oceanic crust formed through backarc spreading and the thicker arc-like basement of the northern GB must occur in the region between our seismic profiles in the backarc off Martinique. This is coherent with the boundary of the region of oceanic crust identified in magnetic data sets (Fig. 2C).

IMPLICATIONS

From our synthesis of magnetic and seismic data in the eastern Caribbean, together with a consideration of regional magmatic ages and tectono-magmatic affinities, we propose a new model for the development of the Lesser Antilles Arc (Fig. 4).

Slab roll-back from ca. 59 Ma triggered extinction of the Aves Ridge and the eastward migration of the arc front. Thick crust, likely formed along the GAC, which underlies the northern GB, implies that upper-plate extension here was insufficient to trigger backarc spreading. South of the modern-day location of the island of Dominica, a north-south–striking spreading ridge created a new backarc basin up to 250 km across. This opening was probably facilitated by the large strike-slip fault systems of the South American margin (e.g., the San Sebastian [offshore Venezuela] and El Pilar [northern Venezuela] faults; Pindell and Kennan, 2009), in marked contrast to the collisional boundary between the northern Caribbean and the Bahamas Bank. Between ca. 40 and 25 Ma, the outer arc was formed, although only the northern part is exposed today as the islands of the Limestone Caribbees.

Post–25 Ma, the arc migrated westward into its own backarc, obscuring the southern spreading center and separating the TB from the southern GB. This resulted in a notable difference in the late Miocene sedimentary succession of the two basins (Aitken et al., 2011). The presence of thick backarc sediments in the south provides a possible explanation for some of the isotopic systematics of the southern LAA magmas, which cannot be explained by sediment contributions from the downgoing plate alone, and which require sediment assimilation during differentiation within the crust (Bezard et al., 2014; Davidson and Harmon, 1989).

We interpret the Cenozoic history of back-and-forth arc jumps as externally driven by the interaction between the Caribbean and adjacent North and South American plates. The western Atlantic lacks the large-scale, downgoing plate buoyant topography that is held responsible for regionally flattening the slab and arc migration in continental arcs such as South America (Martinod et al., 2013). Small features such as the Barracuda and Tiburon Ridges, which are being subducted beneath the LAA today, are likely insufficient to cause whole arc migration (Gerya et al., 2009), particularly if the subduction system is driven by far-field forcing (Martinod et al., 2013) from the westward motion of North and South America past the Caribbean. Instead, changes in the motions of the Americas could have driven slab shallowing, thus triggering westward advancement of the arc. An increase in North American–South American convergence and the eastward motion of the arc beyond the large boundary faults of the South American continent (Boschman et al., 2014) might have contributed to readjustment of the arc position.

We believe that this is the first observed case of the regional-scale migration of an intra-oceanic magmatic arc away from the incoming plate. As well as shedding new light on the tectonic history of the eastern Caribbean region, these results have significant implications for our understanding of the behavior of intra-oceanic subduction zones, and in particular highly constrained subduction systems such as the LAA.

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