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 towards and away from the incoming plate. In oceanic arc systems however, whilst slab roll-back and the associated processes of back-arc spreading and arc migration towards 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 synthesise new evidence to show two phases of back-arc spreading and eastward arc migration towards the incoming Atlantic. A third and final phase of arc migration to the west subdivided the earlier back-arc basin on either side of the present-day Lesser Antilles Arc. This is the first example of regional multi-directional arc migration in an intra-oceanic setting and has implications for along-arc structural and geochemical variations. The back and forth arc migrations are probably due to the constraints the neighbouring American plates impose 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 back-arc spreading, generally due to slab roll-back, arcs often split into an extinct and active arc ([Karig, 1974](#_ENREF_12)). This results in the movement of both the trench and active magmatic front towards 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 kilometres is often accompanied by (temporary) arc shutdown, e.g. [Gerya et al. (2009)](#_ENREF_8). Such events are commonly attributed to the subduction of large buoyant features such as extinct mid-ocean ridges or plateaus that results in a flattening of the slab ([Gerya et al., 2009](#_ENREF_8); [Martinod et al., 2013](#_ENREF_14)).

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 ~59 Ma ([Neill et al., 2011](#_ENREF_17)). Arc magmatism from 40 Ma is found on the islands of the Limestone Caribbees (LC) along the north eastern Caribbean plate boundary. Despite a record of various early Paleocene to Eocene subduction-related rocks tracking migration eastward through the Greater Antilles towards the Virgin Islands ([Cox et al., 1977](#_ENREF_6); [Jolly et al., 1998](#_ENREF_11)), convincing evidence for back-arc 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](#_ENREF_3)). It has even been suggested that the GB is an extended fore-arc, leaving its role in arc migration in the Palaeogene highly uncertain (Aitken et al. 2011). A further unknown is the location of the southern arc during this time. [Speed et al. (1993)](#_ENREF_20) recognised the need for a source of volcanic sediment here during the Eocene and Oligocene, yet 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 LC 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](#_ENREF_15)). 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 (~59 Ma) and the initiation of LAA volcanism at ~25 Ma ([Aitken et al., 2011](#_ENREF_1); [Bird et al., 1999](#_ENREF_3)).

In this study we combine new magnetic (Fig. 2) and seismic (Fig. 3) datasets acquired in the GB in 2016/17 with existing geophysical, geological and geochronological data to test current models for the development of the LAA. We propose a new model for the tectonic evolution of the region in which the Eocene magmatism (of which the LC 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 back-arc into the Grenada and Tobago (TB) Basins. The model explains several of the disputed aspects of the region’s development and is more consistent with current geodynamical models of subduction behaviour. 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.

**A 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 in supplement) and is a significant improvement on existing charts for the region ([Ghosh et al., 1984](#_ENREF_9)). Two of these cruises, JC133 and JC149, conducted as part of the VoiLA (Volatile Recycling in the Lesser Antilles) project also acquired north-south oriented multi-channel seismic reflection and wide-angle refraction profiles in the GB (Fig. 3). Wide-angle profiles, (full processing details in supplement) were modelled using the software RAYINVR ([Zelt and Smith, 1992](#_ENREF_24)), and together these datasets 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 LC. However, rather than merging with the modern arc around Martinique as in current tectonic models, it extends southwards as an unbroken arc, buried beneath the thick sediment of the Barbados Accretionary Prism (BAP). This “Outer Arc” magnetic anomaly passes ~15 km west of the island of Barbados and the so-called Tobago-Barbados Ridge (TBR, Fig. 1), both of which are thought to be uplifted sections of prism sediments ([Gomez et al., 2018](#_ENREF_10)). Given its depth of burial (in excess of 10km, making gravity modelling and seismic imaging of the basement crust difficult), it is its 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 LC arc magmatism along the whole front of the eastern Caribbean plate boundary during the late Paleogene.

A region of dominantly reverse polarity is visible either side of the LAA within the southern GB and TB extending as far north as Dominica/Martinique (Fig. 2). This regional reverse polarity is consistent with slow back-arc opening in the over-riding plate during the dominantly reverse 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 back-arc basin into the GB and TB. A common origin for these two basins has been proposed previously ([Aitken et al., 2011](#_ENREF_1)). 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 back-arc spreading.

Back-arc 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, c. 50-46 Ma: Speed et al., 1993, see supplementary section 3b for further details). The chemical and isotopic composition of these rocks is consistent with a depleted back-arc source ([Speed and Walker, 1991](#_ENREF_21); [White et al., 2017](#_ENREF_23)). Paleocene to mid-Eocene xenocrystic and detrital zircons found throughout the Grenadines possess a rare earth element composition that suggests they crystallised from magma produced from a much less oxidised mantle than the sources of the modern arc, again consistent with a back-arc origin ([Rojas-Agramonte et al., 2017](#_ENREF_19)).

Wide-angle seismic data (Profile 4 - Fig. 3f) further supports our interpretation of back-arc 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)](#_ENREF_5) in the far south of the basin and is likely to extend as far north as southern Martinique. Our new seismic reflection data shows a smoothly undulating basement surface (Fig 3), with no evidence for an E-W striking spreading centre as previously suggested, e.g. [Pindell and Kennan (2009)](#_ENREF_18).

In the northern GB the crust thickens northward from 15 to ~27 km (Fig. 3e). Wide-angle modelling 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)](#_ENREF_13) near Guadeloupe. This crustal thickness rules out back-arc spreading and we interpret it as resulting from older arc magmatism in the over-riding 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 over-riding plate and GAC magmatism. In contrast to the southern LAA, the islands of the northern LAA developed upon this older arc crust. Support from 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](#_ENREF_16)).

The transition between oceanic crust formed through back-arc spreading, and the thicker arc-like basement of the northern GB must occur in the region between our seismic profiles in the back-arc off Martinique. This is coherent with the boundary of the region of oceanic crust identified in magnetics (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 rollback from ~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 back-arc spreading. South of the modern-day location of the island of Dominica, a N-S striking spreading ridge created a new back-arc 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 and El Pilar Faults, Pindell and Kennan, 2009) in marked contrast to the collisional boundary between the northern Caribbean and the Bahamas Bank. Between ~40 and 25 Ma the Outer Arc was formed, although only the northern part is exposed today as the islands of the LC.

Post 25 Ma, the arc migrated westward into its own back-arc, obscuring the southern spreading centre 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](#_ENREF_1)). The presence of thick back-arc 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 down-going plate alone and, require sediment assimilation during differentiation within the crust ([Bezard et al., 2014](#_ENREF_2); [Davidson and Harmon, 1989](#_ENREF_7)).

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, down-going 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](#_ENREF_14)). Small features such as the Barracuda and Tiburon ridges that are being subducted beneath the LAA today, are likely insufficient to cause whole arc migration ([Gerya et al., 2009](#_ENREF_8)), particularly if the subduction system is driven by far field forcing ([Martinod et al., 2013](#_ENREF_14)) from the westward motion of North and South America past the Caribbean. Instead changes in motions of the Americas could have driven slab shallowing, thus triggering westward advance 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](#_ENREF_4)) 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 behaviour of intra-oceanic subduction zones, and in particular highly constrained subduction systems such as the LAA.

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**FIGURE CAPTIONS**

Figure 1. A) Map of the Lesser Antilles region highlighting 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. B) Temporal framework of arc magmatism in the eastern Caribbean. Full breakdown of tectono-magmatic affinities and geochronology provided in the supplementary section 3 (Fig. S8). The Geomagnetic Polarity Timescale is shown for reference.

Figure 2. Magnetic and gravity data for the Caribbean region. A) New regional magnetic anomaly grid. CLIP = Caribbean Large Igneous Province 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 back arc spreading. Bb = Barbados C) Cartoon of key features in anomaly grid over LAA. Regions of normal magnetic anomaly polarity are shown in orange, reverse in blue. D) Cross-section through magnetic grid along profile shown in 2A. Magnetic highs are associated with the Aves Ridge/Great Arc of the Caribbean (GAC), LAA and Outer Arc magmatism. Note the symmetrical spreading anomalies in the Aves Ridge back-arc and Grenada Basin (labelled 1-1’ etc.). TB = Tobago Basin. OA = Outer Arc.

Figure 3. Crustal structure of the Grenada Basin (GB) A) Location of seismic reflection/refraction profiles (green) shot by the VoiLA project as part of JC149. Dashed white sections show subset of reflection profiles plotted in 3B, C. Orange profile gar1 from the Garanti 2017 experiment (Lebrun, pers. comm.). Travel times from this experiment supplemented our own dataset for wide-angle modelling at long offsets along profile 58. B) Section of 2d seismic profile 58 in the northern GB. C) Section of 2d seismic profile 4 in the southern GB. D) 1-D velocity profiles at 3 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](#_ENREF_22)). E) P-wave velocity model for VoiLA project profile 58 in the northern GB, 1 in 10 of modelled rays are shown. UC = upper crust, LC = Lower Crust. F) P-wave velocity model for VoiLA project profile 4 in the southern GB.

Figure 4. Cartoon of new tectonic model for the eastern Caribbean region. Locations of key tectonic blocks based upon the reconstruction of [Boschman et al. (2014)](#_ENREF_4" \o "Boschman, 2014 #363). 60 Ma: Regional arc magmatism associated with 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 dredged samples from the Aves Ridge. CLIP = Caribbean Large Igneous Province. 40 Ma: Slab rollback has led to the abandonment of the Aves Ridge and eastward migration of arc volcanism. The new Outer arc includes the islands of the Limestone Caribbees in the north. Back-arc spreaing is limited to the south with a N-S oriented spreading axis. 0 Ma: Slab shallowing forces the abandonment of the Outer Arc and establishment of the modern Lesser Antilles Arc (LAA) to the west. Arc volcanism has divided the former back-arc basin into the Tobago (TB) and Grenada (GB) Basins in the south. Direct evidence for the southern extension of the Outer Arc is buried beneath the Barbados Accretionary Prism (BAP).

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