Commentary

Back-arc basins form as regions of extension within the overriding plate at convergent plate boundaries. Continued extension results in a region of oceanic crust forming behind the volcanic arc front at many subduction systems. Depending on the local stress regime, and on how well developed the basin is, the nature of back-arc extension can range from rifting (e.g., the northern Mariana Trough, Yamazaki et al., 2003 and Southern Havre Trough, Wright et al., 1996) to active seafloor spreading, more similar to that observed along mid-ocean ridges (e.g., the southern Mariana Trough, Martinez et al., 2000 and Lau Basin, Bevis et al., 1995).

Over the last few decades our understanding of the key drivers of back-arc basin formation has greatly improved. Subduction systems which experience back-arc extension tend to exhibit a number of common characteristics including an old subducting slab (in excess of 55 My age, though this varies with spreading rate) and steep slab dip (Heuret & Lallemand, 2005; Sdrolias & Müller, 2006). When these criteria are met,
subduction trench axis retreat can often create accommodation space in the overriding plate, thereby driving spreading (Sdrolias & Müller, 2006). In such cases significant compositional and temperature variations may occur within the source mantle, resulting from variations in the amount of (slab-derived) hydrous melt entrained beneath the back-arc, as well as mantle mixing driven by migration of the slab (Eason & Dunn, 2015; Grevemeyer et al., 2020). As a result, globally the structure and composition of back-arc oceanic crust is shown to be extremely diverse, often with significant departures from the typical Penrose-type model of oceanic crust (Grevemeyer et al., 2020).

The Lesser Antilles arc formed as a result of volcanism associated with the westward dipping subduction of Atlantic oceanic crust beneath the overriding Caribbean Plate, with activity along the current arc initiating ~25 Ma. The Grenada Basin is an ~150 × 500 km back-arc basin separating the modern volcanic arc from the now-extinct Aves Ridge to the west (Figure 1.). The Aves Ridge, while poorly sampled, is presumed to represent a now abandoned limb of an older regional arc system known as the Great Arc of the Caribbean active >60 My ago (Christeson et al., 2008; Neill et al., 2011). The opening of the Grenada Basin is generally thought to coincide with the migration of volcanism from this older system to the modern arc during the Paleogene (Boschman et al., 2014; Pindell & Kennan, 2009).

At first glance the Grenada Basin should be an ideal location to observe back-arc extension. The subducting slab has an age in excess of 90 My at the trench (Heuret & Lallemand, 2005), a slab dip of 30–50° (Bengoubou-Valerius et al., 2008; Bie et al., 2020) and an extensive history of migration of the trench axis as the leading edge of the Caribbean plate migrated from the Pacific, where it formed, through to the Atlantic (Boschman et al., 2014; Pindell & Kennan, 2009). Furthermore, as one of only two systems to subduct structurally variable, slow-spreading oceanic crust formed at the Mid-Atlantic Ridge, with extremely slow
subduction convergence rates at the trench as low as 11 mm yr\(^{-1}\), and with the margins of the subduction system unusually constrained by the North and South American continents, the Lesser Antilles should be an important end-member case when it comes to understanding the geodynamics of back-arc spreading. Despite this, up to now the Grenada Basin has made minimal contribution to our understanding of back-arc processes and is often largely ignored in global studies of back-arc/subduction behavior (e.g., Grevemeyer et al., 2020; Heuret & Lallemand, 2005; Stern et al., 2002; Sdrolias & Müller, 2006).

Extreme thicknesses of sediment in the south of the basin, which in places may exceed 12 km as a result of the large sedimentary outflow from the adjacent South American continent (Aitken et al., 2011; Chichester et al., 2020), not only limit the usefulness of potential-field data (particularly gravity surveys), but also make it impossible to directly sample the basement lithology in-situ. The only hard-rock evidence for back-arc spreading comes from mid-Eocene-age pillow basalts sampled on the islands of Mayreau (Mayreau basalt) and Carriacou (Cherry Hill basalt). These outcrops are geochemically consistent with back-arc volcanism and are thought to have been uplifted by subsequent arc activity (Speed et al., 1993; White et al., 2017). Locally, seismic wide-angle surveys, which are generally the most accurate tool for constraining crustal structure in marine regions, have focused on the structure of the Lesser Antilles arc and forearc and are either limited to the outskirts of the Grenada Basin (Christeson et al., 2008; Kopp et al., 2011) or are interrupted by internal maritime boundaries (Allen et al., 2019).

As a result the structure and composition of the crust in the back-arc are very poorly constrained, and a whole host of models for the opening of the Grenada Basin are currently in circulation, not limited to a simple shear basin (Arnaiz-Rodríguez & Audemard, 2018), spreading on a N-S oriented spreading ridge (Allen et al., 2019), spreading on a E-W orientated spreading ridge (Pindell & Barrett, 1990), fan-like distributed spreading (Pindell & Kennan, 2009), and extension within the forearc of the previous Aves Ridge system (Aitken et al., 2019).

Writing in Journal of Geophysical Research: Solid Earth, Padron et al. (2021) present the most detailed geophysical investigation of the structure of the interior of the Grenada Basin to date. As part of the GARANTI project they acquired three regional wide-angle profiles, 30 multichannel seismic profiles as well as corresponding shipboard gravity, magnetic and bathymetry datasets in order to study the structure of the Grenada Basin and eastern Aves Ridge (see also Garrocq et al., 2021). Using these wide-angle profiles, in conjunction with gravity modeling, the authors have been able to clearly map variations in crustal structure across the Grenada Basin, and the nature of the transition between the Aves Ridge, Grenada Basin and Lesser Antilles arc to a degree which had never previously been possible, shedding new light on the mechanics of back-arc spreading at the Lesser Antilles (Figure 1). For the first time this allows for direct comparison between the structure and nature of spreading in the Grenada Basin and more well studied back-arc systems such as those in the Pacific.

In the north of the Grenada Basin (profile GA03 and northern GA01), Padron et al. (2021) observe a 2-layer crust of up to 25 km thickness, with only minor variations in Moho depth and velocity structure between the Aves Ridge, northern Grenada Basin and Lesser Antilles arc. Velocities in the thick lower crustal layer along profile GA03 are not seen to exceed 7 km s\(^{-1}\). This thick crust confirms the long-held presumption that the northern Grenada Basin has experienced little-to-no back-arc extension (and certainly not oceanic-style spreading).

The origin of this thick basement, which seemingly extends throughout much of the NW corner of the Caribbean plate, is more uncertain. Some authors suggest that the Lesser Antilles arc is constructed upon an oceanic plateau similar to the Caribbean Large Igneous Province (CLIP, Evain et al., 2013; Kopp et al., 2011) which leads to crustal thicknesses exceeding 20 km in the central region of the Caribbean plate (Mauffret & Leroy, 1997). If a plume is responsible for the thick crust beneath the northern Grenada Basin, the observed lower crustal velocities of < 7 km s\(^{-1}\) are very low given the amount of crustal thickening which has seemingly taken place and may indicate an unusually fertile or hydrous mantle source composition (similar to observations at the Carnegie Ridge, Sallarès et al., 2005; in comparison, lower crustal velocities beneath the CLIP have been measured in excess of 7.3 km s\(^{-1}\), Mauffret & Leroy, 1997). Alternatively, this thickened crust may be the result of extended periods of local arc volcanism related to the now abandoned Great Arc of the Caribbean (Allen et al., 2019). These models are likely to be difficult to resolve without more direct sampling of the basement compositions both within the Grenada Basin and along the Aves Ridge.
Moving south, the authors observe a rapid shallowing of the mantle. In a 75 × 250 km region south of Dominica, the back-arc crustal thickness is on the order of 6–8 km and lower crustal velocities of up to 7.1 km s−1 are in keeping with oceanic-type crust (Figure 1). This change in basement structure happens rapidly across ~80 km behind the central arc and marks an extremely abrupt transition from a region of seemingly very limited extension in the northern basin, to oceanic spreading in the south. This contrasts with systems such as the Mariana trough, where there is a much more gradual transition from rifting into full oceanic spreading from north to south (Martinez and Fryer, 2000; Yamazaki et al., 2003).

Compared to the recent compilation of back-arc crustal structures presented by Grevemeyer et al. (2020), the crust in the southern Grenada Basin is remarkably similar to that formed at typical fast spreading oceanic ridge, without any of the thickness/velocity anomalies often observed in back-arc crust as a result of heterogeneities in the source mantle. Despite the complex tectonic history of the region this may indicate a surprisingly typical mid-ocean ridge-type mantle composition beneath the southern back-arc, seemingly without any great contribution from hydrous melting as a result of the dehydrating slab (in which case we might expect to observe enhanced melting, with abnormally high crustal thicknesses or the formation of higher velocity lower crustal mafic cumulates, Grevemeyer et al., 2020).

Why there is this very abrupt transition from the thick basement in the north to oceanic spreading in the south may be key to properly understanding the geodynamics of the region; with possible controlling factors including stresses exerted on the borders of the Caribbean plate from North and South America, N-S temperature/compositional variations in the upper mantle, slab dip changes, variations in slab hydration, the subducting North-South American plate boundary, or some combination of the above.

In their southernmost velocity profile (GA02, see Figure 1), the authors liken the width of the transition zone between the thick crust of the Aves Ridge and the oceanic crust of the southern back-arc to a transform margin, suggesting that there may be a strong oblique component to spreading relative to the convergence direction. However, they also note significant asymmetry between the western and eastern margins of the basin with an exceedingly abrupt transition from the oceanic crust of the southern Grenada Basin to the thick crust of the Lesser Antilles arc (Figure 1). This is symptomatic of one of the key uncertainties that remains in our understanding of the history of the Lesser Antilles. Previous studies have theorized that the Grenada Basin, and Tobago (forearc) Basin (Figure 1) formed as a large, continuous structure, which was later divided following local arc migration in the late Paleogene, and the formation of the islands of the southern Lesser Antilles (Aitken et al., 2011; Allen et al., 2019; Speed et al., 1991). These models cite apparent symmetry in sediment structure imaged by multichannel seismic and basement magnetic anomalies either side of the southern arc platform. Such an event may have obscured any spreading ridge in the southern Grenada Basin, while also creating this unusual structural asymmetry across the basin. However, the only modern wide-angle data within the Tobago basin consists of a single profile across its southernmost point (Christeson et al., 2008), making it exceedingly difficult to say definitively whether or not this oceanic crustal domain truly extends beneath the islands of the southern Antilles and beyond into the forearc.

For the first time, the velocity and density profiles presented by Padron et al. (2021), have allowed for clear mapping of crustal domains and compositions throughout the Grenada Basin. These results are a vital step forward in our understanding of the tectonic development of the eastern Caribbean region. While the region has been historically data poor, the complexity of back-arc processes in the Grenada basin, including the very rapid transition from thick basement crust in the north to oceanic spreading in the south, and the apparently oblique nature of extension compared to the convergence direction, certainly highlight why subduction processes at the Lesser Antilles arc are worthy of much more detailed study. While some fundamental uncertainties remain, this end-member subduction system is undeniably a region with much to contribute to our understanding of the complexities of back-arc behavior.

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