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ABSTRACT

It has been proposed that interseismic coupling along the Lesser Antilles subduction interface could be responsible for subsidence observed over the past 125,000 to 100 years inferred from geological data on Quaternary coral terraces and active micro-atolls in the central part of the arc. However, horizontal GNSS velocities show that the Lesser Antilles subduction zone is currently experiencing low interseismic coupling, meaning that little to no elastic strain currently builds up as the North- and South American plates subduct beneath the Caribbean plate. Here we show, using modern geodetic data, a general subsidence of the Lesser Antilles island arc at 1-2 mm/yr over the past 20 years, in agreement with the ~100-year trend of 1.3 ± 1.1 mm/yr subsidence derived from coral micro-atolls in eastern Martinique. Using elastic dislocation models, we show that a locked, or partially locked subduction interface would produce uplift of the island arc, opposite to present-day and recent geological observations, hence supporting a poorly-coupled subduction. This subsidence since at least 125 ka is in line with the extensional tectonics observed along the arc since the mid-Miocene. The margin-wide subsidence is therefore likely controlled by large-scale geodynamic processes that operate over the long-term. Such processes could also play a role in tuning the aseismic character of the subduction megathrust, which appears to be a long-term feature.

INTRODUCTION

The accumulation of stresses along locked subduction interfaces over timescales of tens to hundreds of years (i.e., short-term) leads to horizontal and vertical deformation of the overriding plate (e.g., Savage et al., 1983; Chlieh et al., 2004). Interseismic locking results in landward horizontal motions in the (fore)arc and tectonic subsidence or uplift depending on the distance from the trench and the structure of the overriding plate (e.g., Wallace et al., 2012, Mouslopoulou et al., 2016). Such deformation is largely elastic and is balanced by coseismic and postseismic slip during large earthquake sequences (Avouac, 2015). Monitoring this deformation with geodetic observations therefore provides information about the ability of the subduction interface to generate megathrust earthquakes (e.g., Loveless and Meade, 2011; Avouac, 2015). On longer time scales (i.e., from ten thousand to several million years), convergence at subduction zones leads to anelastic deformation of the overriding plate, resulting in processes such as mountain building (e.g., Armijo et al., 2015; Jolivet et al., 2020) or basal erosion or accretion (e.g., Menant et al., 2020, Boucard et al., 2021). As a result, over time scales of tens to hundreds of years plate convergence is not entirely transformed into elastic, recoverable deformation, but part of it must be converted into permanent strain. Understanding the interplay between such short- and long-term deformation patterns and how their underlying processes tune the present-day seismogenic behavior of subduction zones is fundamental for seismic hazard assessment in such contexts.

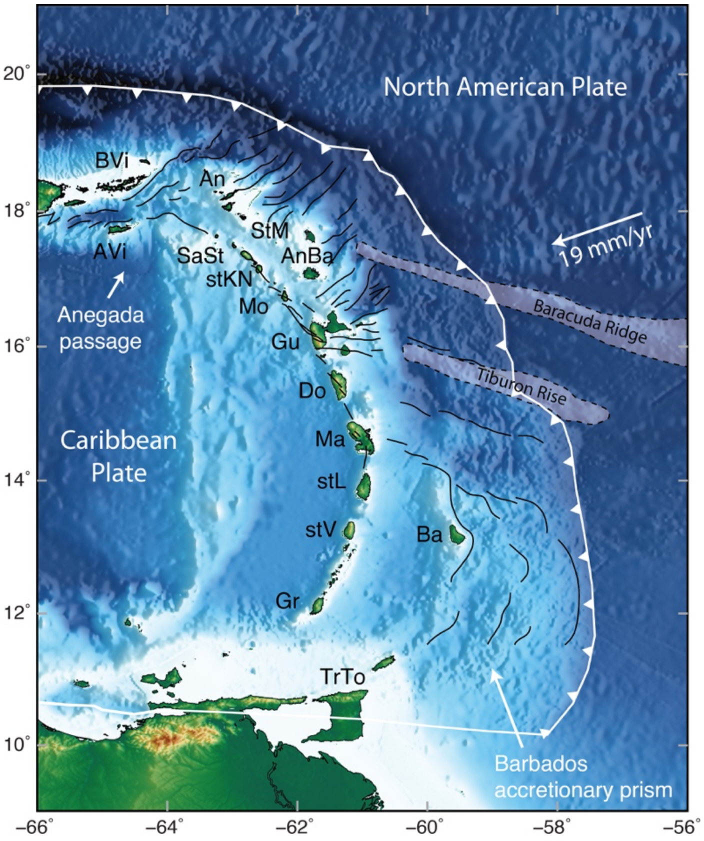

Figure 1. Seismotectonic setting of Lesser Antilles subduction zone. BVI, British Virgin Islands; AVI, American Virgin Islands; An, Anguilla; stM, Saint Martin; SaSt, Saba & Saint Eustatius; AnBa, Antigua & Barbuda; stKN, Saint Kitts & Nevis; Mo, Montserrat; Gu, Guadeloupe; Do, Dominica; Ma, Martinique; stL, Saint Lucia; stV, Saint Vincent; Gr, Grenada; Ba, Barbados; TrTo, Trinidad & Tobago.

Lesser Antilles subduction zone, which constitutes the eastern boundary of the Caribbean plate (Figure 1), has not experienced any large megathrust earthquakes in the past 100 years (Stein et al., 1989). Two large historical earthquakes in the 19th century (M7-8 in 1839 and M7.5-8.5 in 1843) have been interpreted by some as thrust events, but unequivocal evidence for this is missing (e.g., Bernard and Lambert, 1988). Caribbean-wide geodetic studies over the past decade all found low interseismic coupling of the subduction interface (Manaker et al., 2008; Symithe et al., 2015), a finding recently confirmed by a more detailed study focused on the Lesser Antilles (van Rijsingen et al., 2021). Their Bayesian inversion of horizontal GNSS velocities and forward models show that the subduction interface is currently unlocked, with no re-locking of the proposed rupture areas of the 1839-1843 earthquakes. These results however cover the last few decades only; expanding temporal coverage over one or several seismic cycles requires geological proxies such as coral data (e.g., Sieh et al., 2008).

Micro-atoll data collected in Martinique (Weil-Accardo et al., 2016) indicate tectonic subsidence at 1.3 ± 1.1 mm/yr since 1895, while estimates from reef terraces in Les Saintes (part of the archipelago of Guadeloupe; Leclerc et al. 2014) and Martinique (Leclerc et al., 2015) indicate subsidence at 0.3-0.45 mm/yr over the past 125 ka. Therefore, at least the central part of the Lesser Antilles arc has been experiencing tectonic subsidence over this time interval, an observation that has been related to temporal variations in friction of an overall locked plate interface, or to the accumulation of coseismic deformation from megathrusts earthquakes not compensated by opposite interseismic uplift (Leclerc & Feuilet, 2019).

Here we use data from continuously operating GNSS stations in the Lesser Antilles to show that the island arc is currently experiencing margin-wide subsidence at 1-2 mm/yr, in agreement with observations from corals. We show such subsidence does not represent a fraction of the elastic strain observed during the interseismic period over a locked subduction interface. These results therefore suggest that the arc subsidence observed across several time-scales (up to ~20 years for GNSS, 10s-100s years for micro-atolls, 10^3 to 10^4 years for marine terraces) is controlled by lithosphere-scale geodynamic processes and is independent from elastic deformation within the earthquake cycle.

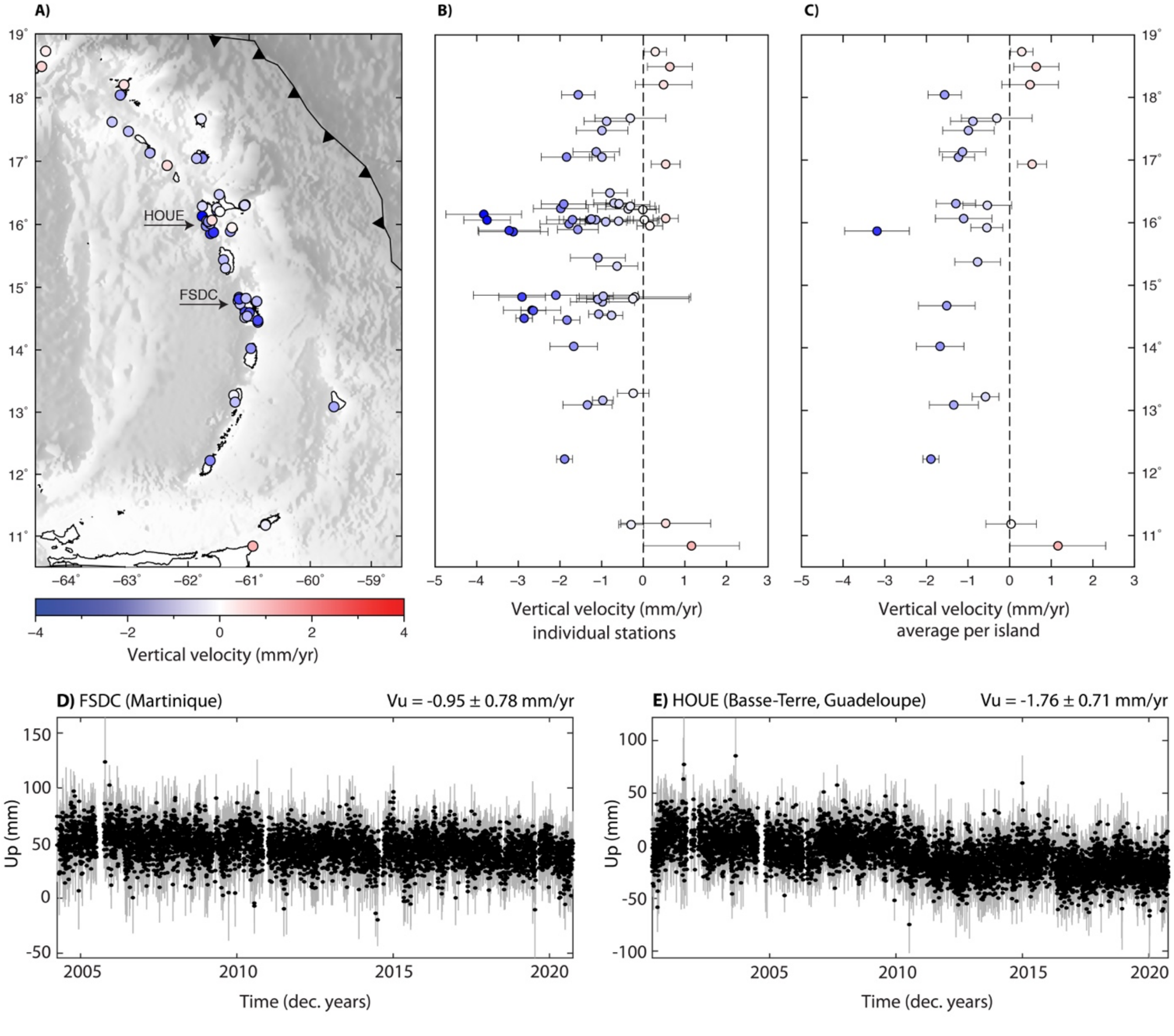

Figure 2. Vertical tectonic motions of the Lesser Antilles islands. A) Vertical velocity per GNSS station in map view. B) Vertical velocities ordered by latitude (vertical axis) and amplitude (horizontal axis). C)

Average velocity per island, calculated as a weighted average based on the time series length. D) Time series vertical component station FSDC (Martinique). E) Time series vertical component station HOUE (Basse-Terre, Guadeloupe).

VERTICAL GNSS CONFIRMS UNCOUPLED SUBDUCTION INTERFACE

The GNSS data used in this study were processed as described in van Rijsingen et al. (2021), with longer time series so as to covers the 1994-2020 time interval. The vertical velocities used in this paper were computed using a least-squares fit of the data with a functional form that includes a linear trend, seasonal and semi-seasonal oscillations, and step functions at times when offsets are reported (equipment change or local earthquakes) or visually detected. We used the First-Order Gauss-Markov Extrapolation algorithm (Herring, 2003; Reilinger et al., 2006) to obtain velocity uncertainties that account for time-correlated noise in the time series.

Vertical motions at the 53 GNSS stations with at least three years of continuous data (Figure 2A) show a general pattern of subsidence of the Lesser Antilles, while islands at the edges of the subduction (i.e., the Virgin Islands in the North and Trinidad in the South) show uplift. The islands of Guadeloupe and Martinique, for which station density is highest, show subsidence rates between 0 ± 0.3 to 3.8 ± 0.9 mm/yr (Figure 2B), in good agreement with a recent study by Sakic et al. (2020) who found similar vertical velocities from two independent geodetic solutions. The variability likely results from local site conditions, but mostly from variations in time series duration amongst GNSS stations. We therefore use the time series duration to calculate a weighted average for each island (Figure 2C) and find a homogeneous pattern of subsidence at 1-2 mm/yr along the arc, with an overall average rate of 1.1 ± 0.6 mm/yr. This subsidence is in agreement with observations from micro-atolls in Martinique over the past 125 years (i.e., 1.3 ± 1.1 mm/yr;

Weil-Accardo et al., 2016), and has an amplitude similar to that observed at other subduction zones (e.g., Vannucchi et al., 2013). The subsidence derived from micro-atolls has been interpreted as the result of interseismic locking of the subduction interface or coseismic displacements during megathrust earthquakes (Weil-Accardo et al., 2016; Leclerc et al., 2015). However, the agreement between the "geological" subsidence and the "geodetic" one, while the subduction interface currently has very low interseismic coupling (van Rijsingen et al., 2021), is an indication that they result from processes that are not related to the elastic earthquake deformation cycle. In the following, we therefore calculate how much vertical deformation one should expect from interseismic loading along the plate interface using forward models with various interseismic locking depths.

We use the model setup of van Rijsingen et al. (2021), which uses the Slab2 geometry (Hayes et al., 2018) and a layered semi-infinite elastic medium (Zhu and Rivera, 2002) based on Schlaphorst et al. (2018). We test three different scenarios of homogeneous interplate locking, using downdip limits of the seismogenic zone at 20, 40 and 65 km (Figure 3). Using these locking patterns, we calculate vertical deformation at the locations of GNSS stations along the arc. As can be observed in Figure 3A, a shallow locking down to 20 km does not result in any significant vertical deformation at most of the islands, a consequence of their large distance to the locked portion of the subduction interface. Increasing the downdip limit of the locked interface to 40 km (Figure 3B) results in uplift of most islands at rates of 1-2 mm/yr. Only some islands in the South, such as Saint Vincent, the Grenadines and Grenada, where the slab dip is shallower and the arc is thus located further away from the trench, do not show any uplift or subsidence. The third scenario, a homogeneously locked interface down to 65 km depth, proposed by Bie et al. (2020), is a deep end-member compared to the global range (51±9 km; Heuret et al., 2011). This model shows subsidence at the islands located above the coupled area (i.e., from south to north: Tobago, Barbados, Basse-Terre, La Désirade, Antigua, Barbuda, Anguilla, and Saint Martin) and uplift at 0.2 to 1.3 mm/yr further west along the present-day volcanic arc (Figure 3C). We find results similar to those described above when performing the forward model calculations for an alternative slab geometry (Bie et al.,2020), which becomes steeper at larger depths compared to the Slab2 model (Figure S1).

This simple experiment leads to two conclusions. First, we observe that deep or intermediate interseismic locking of the plate interface would result in present-day uplift of the islands at rates that would be detectable by GNSS (Figure 3), whereas geodetic and micro-atoll observations both show subsidence in the 1-2 mm/yr range (Figure 2A). This is an additional argument in favor of a largely uncoupled Lesser Antilles subduction interface, consistent with the low interseismic coupling found using horizontal geodetic velocities only (van Rijsingen et al., 2021). Second, as the three locking scenarios tested here contradict the observation of present-day subsidence of the entire Lesser Antilles arc, we infer that such subsidence is not the result of seismic cycle-related processes but rather of longer-term processes, which will be discussed below.

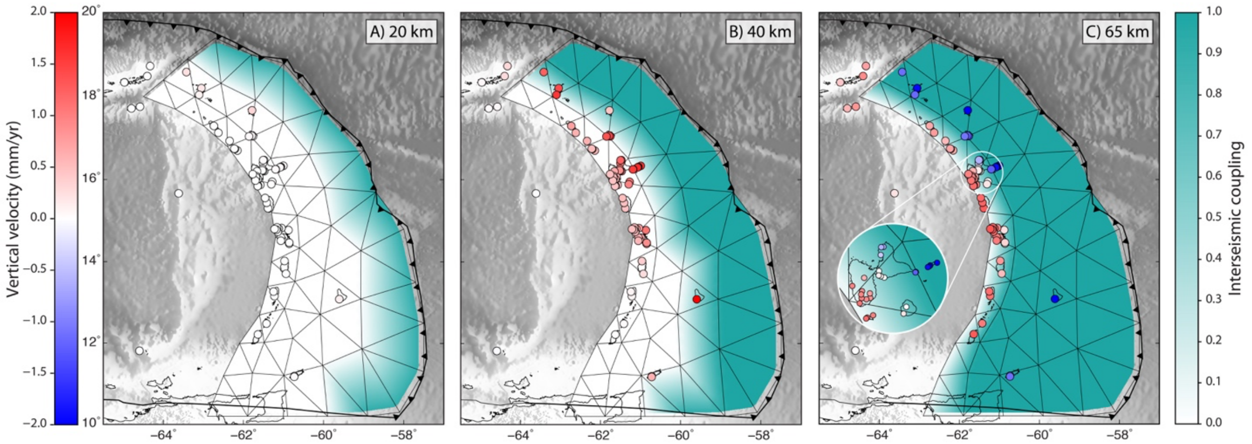

Figure 3. Predicted vertical motions for three scenarios of interseismic coupling: a downdip locking limit of 20 km (A), 40 km (B), and 65 km (C). The inset in C shows the transition from predicted subsidence to uplift from NE to SW for the Guadeloupe Archipelago.

LONG-TERM SUBSIDENCE ALONG THE ENTIRE MARGIN

Figure 4 summarizes the observations of tectonic subsidence in the Lesser Antilles over a range of time scales. We observe a long-term subsidence trend, though the rate derived from reef terraces over 125 ka is smaller than the more recent observations from micro-atolls and GNSS observations. This could indicate an increase in subsidence rate since the last hundreds of thousands of years, as suggested by Leclerc and Feuillet (2019). As this general subsidence cannot be attributed to interseismic loading along the subduction megathrust, one must look into longer-term processes. For instance, crustal faulting and volcano-related deformation (e.g., magmatic chamber cooling or loading of volcanic edifices) may contribute to the observed subsidence, although at rates that are too small to explain the observed amplitudes of 1-2 mm/yr (e.g., Leclerc and Feuillet 2019). Variations in vertical motions between islands could also be attributed to an interplay between local and regional deformation processes. This is probably the case for La Désirade (a small island part of the Guadeloupe Archipelago) that has undergone substantial uplift in the Calabrian, followed by a decrease to negligible rates since 122 ka possibly due to the transient influence of the subducting Tiburon ridge (Figure 4; Léticée et al., 2019).

To better understand the apparent long-term, margin-wide subsidence of the Lesser Antilles, one needs to zoom out and consider the geodynamic and tectonic context of the whole region. Since the late Eocene (~38 Ma), two main extensional phases occurred, first in a trench-parallel direction, followed by trench-perpendicular extension that appears to be still active today (e.g., Boucard et al., 2021). The trench-parallel extension most likely occurred in response to collision of the Bahamas Bank with the Northeastern Caribbean Plate in late Paleocene-early Eocene times (~56 Ma), which caused a major plate reorganization, followed by progressive bending of the Lesser Antilles trench into its current convex geometry (Cornée et al., 2021). The arc-perpendicular V-shaped basins that formed in response to this are currently sealed and cross-cut by transverse faults that accommodate ongoing arc-perpendicular extension since the mid-Miocene (Boucard et al., 2021). This second phase of extension is chronologically consistent with regional subsidence in the northern- (forearc; Boucard et al., 2021, intra-arc; Cornée et al., 2021), central- (offshore Guadeloupe; De Min et al., 2015) and southern part of the margin (back-arc basin; Garrocq et al., 2021). It is possible that the tectonic subsidence discussed here (Figure 4) for the more recent times, including the Present, is the result of the on-going continuation of this post-mid-Miocene extension.

In terms of processes, Boucard et al. (2021) argue that tectonic erosion is responsible for the forearc subsidence, as well as for the landward migration of the Northern Lesser Antilles Arc from mid-Miocene to Early Pliocene. Although such mechanism could play a role in the Northern Lesser

Antilles, where the incoming plate is relatively rough, the 7-km-thick pile of trench sediments in the South would certainly overcome any material lost by tectonic erosion (De Min et al., 2015). Such discrepancy should result in along-arc variability of the subsidence rate that we do not observe. In addition, tectonic erosion generally occurs within several kilometers of the trench (Regalla et al., 2013), whereas the Lesser Antilles islands are located at > 170 km from the trench. Alternatively, we suggest that the observed trench-perpendicular extension and margin-wide subsidence are controlled by slab dynamics processes. Since the trench-perpendicular extension (and related margin-wide subsidence) and the landward migration of the arc overlap in time (i.e., from middle Miocene to Early Pliocene), a simple shallowing or steepening of the slab would not explain both observations. More complex processes, such as slab unbending, or changes in slab buoyancy would then be a plausible explanation (Buiter et al., 2001; Regalla et al., 2013). Such processes could also play a role in tuning the aseismic character of the subduction megathrust (Beall et al., 2021), which appears to be a longer-term feature.

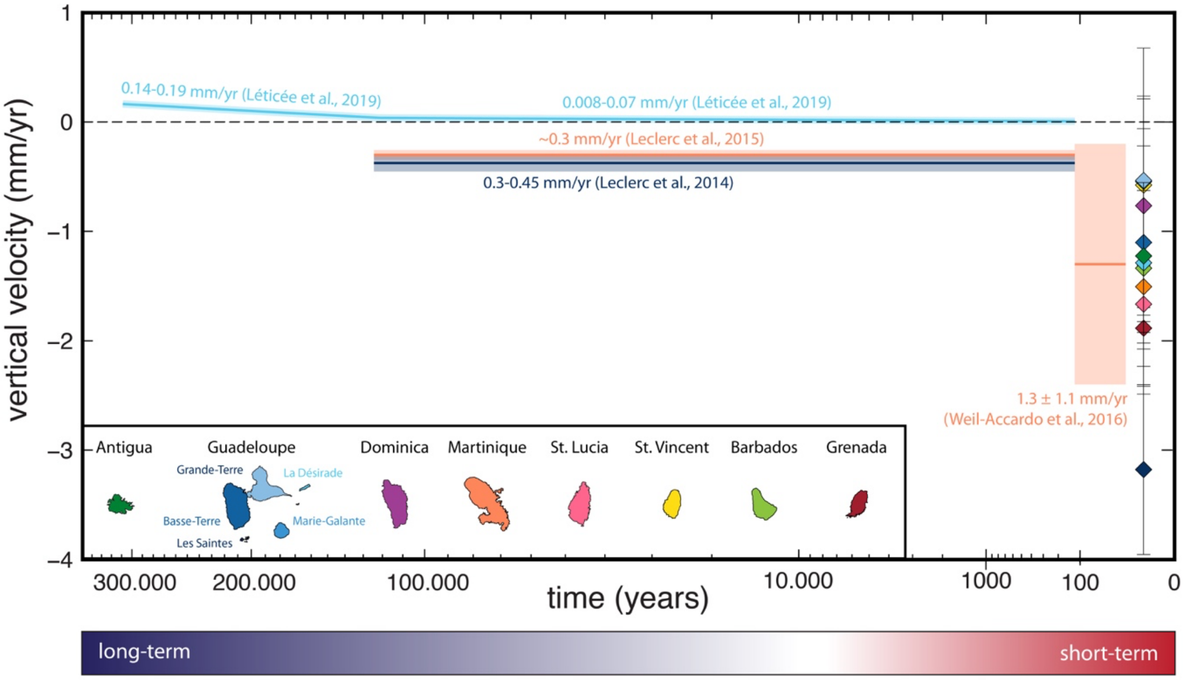

Figure 4. Overview of vertical tectonic motions on different time-scales, ranging from several tens of years (right) to hundreds of thousands of years (left) and color-coded per island. Diamond symbols indicate the weighted average velocities for all islands (modern geodesy; this study), while lines indicate estimates from micro-atoll data (Weil-Accardo et al., 2016) and reef terraces (Leclerc et al., 2014; 2015, Léticée et al., 2019).

ACKNOWLEDGMENTS

We thank Serge Lallemand and Boris Marcaillou for helpful discussions. EvR and GNSS campaigns were supported through the FEDER European Community program within the Interreg Caraïbes "PREST" project and EC and RJ acknowledge support from the Institut Universitaire de France. This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (Grant Agreement 758210, Geo4D project).

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