Ongoing tectonic subsidence in the Lesser Antilles subduction zone

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Summary

Geological estimates of vertical motions in the central part of the Lesser Antilles show subsidence on timescales ranging from 125.000 to 100 years, which has been interpreted to be caused by interseismic locking along the subduction megathrust. However, horizontal GNSS velocities show that the Lesser Antilles subduction interface is currently building up little to no elastic strain. Here we present new present-day vertical velocities for the Lesser Antilles islands and explore the link between short- and long-term vertical motions and their underlying processes. We find a geodetic subsidence of the Lesser Antilles island arc at 1-2 mm/yr, consistent with the ~100-year trend derived from coral micro-atolls. Using elastic dislocation models, we show that a locked or partially-locked subduction interface would produce uplift of the island arc, opposite to the observations, hence supporting a poorly-coupled subduction. We propose that this long-term, margin-wide subsidence is controlled by slab dynamic processes, such as slab rollback. Such processes could also be responsible for the aseismic character of the subduction megathrust.

Key words

Lesser Antilles, Vertical tectonic motions, seismotectonics, subduction, subsidence, earthquakes

1. Introduction

The accumulation of stress 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). This interseismic deformation is typically assumed to be elastic, to be released by earthquakes along the subduction megathrust (i.e., coseismic slip), as well as by postseismic processes (i.e., afterslip and viscous relaxation; e.g., Avouac, 2015, Hu et al., 2016). Monitoring the degree of locking along the subduction interface with geodetic measurements therefore provides information on its ability to generate large ($M_w > 7.5$) megathrust earthquakes (e.g., Loveless and Meade, 2011; Avouac, 2015).

In contrast to short-term interseismic deformation, convergence at subduction zones on time scales from ten thousand to several million years (i.e., long-term), 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., Heki 2004, 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 accommodated by elastic, recoverable deformation, but part of it is converted into permanent strain. Understanding the interplay between such short- and long-term deformation patterns and how their underlying processes influence the seismogenic behavior of subduction zones is fundamental for seismic hazard assessment in such contexts.

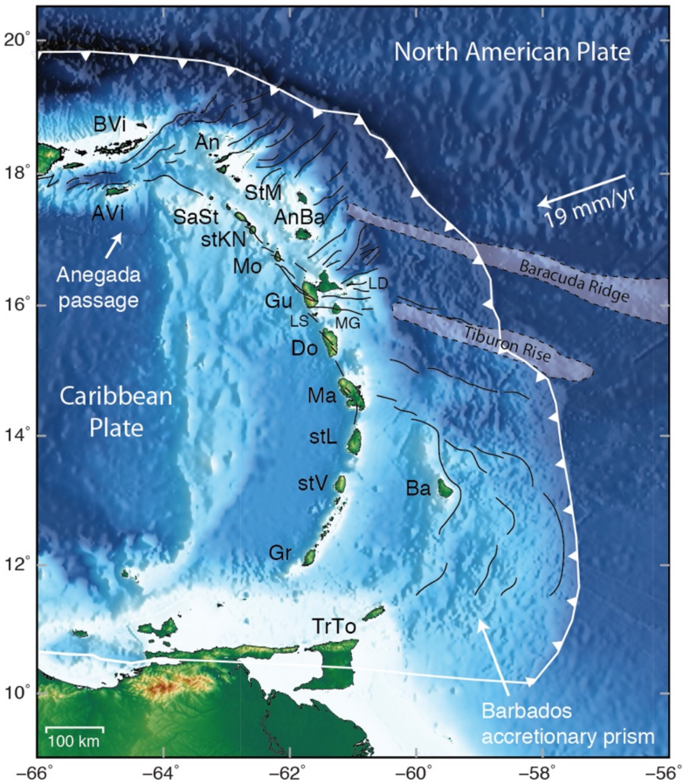

Figure 1. Seismotectonic setting of Lesser Antilles subduction zone. BVI, British Virgin Islands; AVI, American Virgin Islands; An, Anguilla; stM, Saint Martin; SaSt, Saba & Saint Eustatius; AnBa, Antigua & Barbuda; stKN, Saint Kitts & Nevis; Mo, Montserrat; Gu, Guadeloupe; LS, Les Saintes; MG, Marie Galante; LD, La Désirade; Do, Dominica; Ma, Martinique; stL, Saint Lucia; stV, Saint Vincent; Gr, Grenada; Ba, Barbados; TrTo, Trinidad & Tobago. Plate motion vector shows North America with respect to Caribbean from Symithe et al. (2015).

The Lesser Antilles subduction zone, which constitutes the eastern boundary of the Caribbean plate (Fig. 1), has not experienced any thrust events larger than $M_W > 6.5$ 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). Coastal stratigraphy records of the past 5000 years reveal no tsunami deposits related to arc-wide, megathrust events, suggesting that such events either had a very low frequency, or were absent during the Holocene (Paris et al., 2021). 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 inversion of horizontal GNSS velocities and forward models show that the subduction interface is currently poorly coupled, with no re-locking of the proposed rupture areas of the 1839-1843 earthquakes. The active plate margin is thus apparently not building up elastic strain at a significant rate today. GNSS velocities typically cover the last few decades only, so expanding temporal coverage over one or several seismic cycles requires geological proxies such as coral data (e.g., Sieh et al., 2008, Philibosian et al., 2017).

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, Fig. 1; Leclerc et al. 2014) and Martinique (Leclerc et al., 2015) indicate subsidence at 0.3-0.45 mm/yr over the past 125 ka. Recent micro-atoll results north of Martinique, covering ~25-85 years in the 20th century and encompassing the region between Marie Galante and Barbuda show subsidence at 0.3 to 8 mm/yr (Philibosian et al., 2022). Therefore, at least the central and northern parts of the Lesser Antilles arc have 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 megathrust earthquakes that would not be fully compensated by opposite interseismic uplift (Leclerc & Feuilet, 2019). This interpretation is however inconsistent with the low interseismic coupling inferred from horizontal GNSS data covering the last few decades, which raises the question of how horizontal and vertical deformation of the Lesser Antilles (fore)arc are related over these timescales.

Here, we use data on vertical velocities 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 cannot be caused by the build-up of elastic strain during the interseismic period over a locked, or partially 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 long-term lithosphere-scale processes.

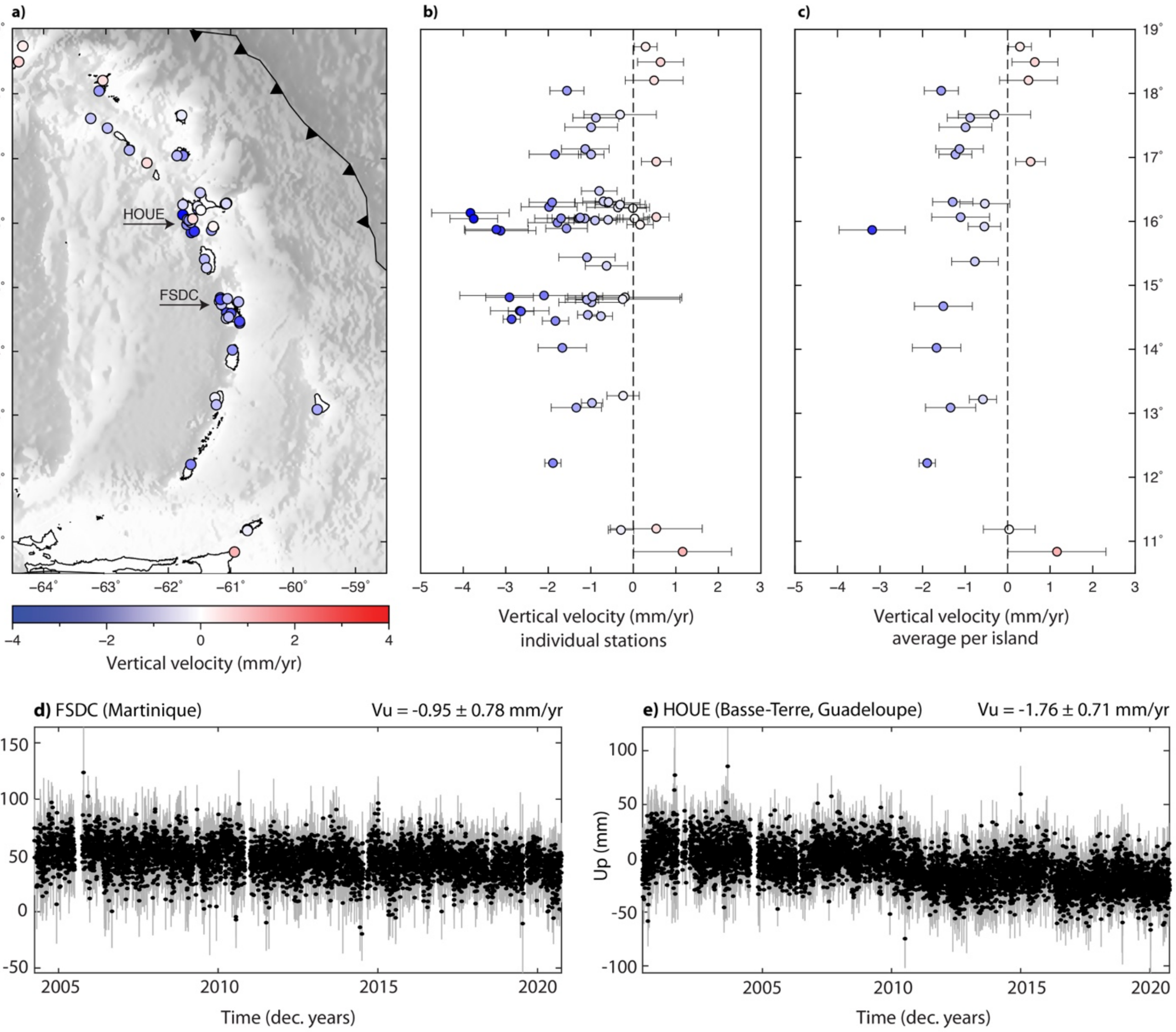

Figure 2. Vertical tectonic motions of the Lesser Antilles islands. a) Vertical velocity of GNSS stations in map view. b) Vertical velocities (horizontal axis) ordered by latitude (vertical axis). c) Average velocity per island, calculated as a weighted average based on the time series length. d) Time series of the vertical component of GNSS station FSDC (Martinique). e) Time series of the vertical component of GNSS station HOUE (Basse-Terre, Guadeloupe).

2. 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 cover the 1994-2020 time interval. The vertical velocities 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 (Fig. 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 from 0 ± 0.3 to 3.8 ± 0.9 mm/yr (Fig. 2b), in good agreement with a recent study by Sakic et al. (2020) who found similar vertical velocities from two independent geodetic solutions (Fig. S1, Table S3). The variability likely results from variations in time series duration amongst GNSS stations and between solutions. We therefore use the time series duration to calculate a weighted average for each island (Fig. 2c; supporting information) 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 where subsidence is also currently observed (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 (Leclerc et al., 2015, Weil-Accardo et al., 2016, Philibosian et al., 2022). However, the agreement between the "geological" subsidence and the "geodetic" one, while the subduction interface currently has very low interseismic coupling (i.e., a coupling coefficient ≤0.2 in the 0-65 km depth range; van Rijsingen et al., 2021), is an indication that subsidence does not result from processes 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 six different scenarios of homogeneous full or partial interplate locking, using downdip limits of the seismogenic zone at 20, 40 and 65 km (Fig. 3 and Fig. S2, respectively). Using these locking patterns, we calculate predicted vertical velocities at the locations of GNSS stations along the arc. As can be observed in Fig 3a, a shallow locking down to 20 km does not result in significant vertical motion 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 (Fig 3b) results in uplift of most islands at rates of 1-2 mm/yr for the full locking scenario. 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 uplift or subsidence. The third scenario, a homogeneously locked interface down to 65 km depth (Fig 3c), as 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 (Figs 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 (Fig. S3). Forward models in which we explore a smoother transition from the coupled to the non-coupled region at depth (Fig. S4) similarly predict uplift at almost all islands.

From these forward model experiments we can draw two conclusions. First, 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 (Fig. 3), whereas geodetic and micro-atoll observations both show subsidence in the 1-2 mm/yr range (Fig. 2a). This is an additional argument in favor of a largely uncoupled Lesser Antilles subduction interface, consistent with the low (<0.2) 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 tectonics, which will be discussed below.

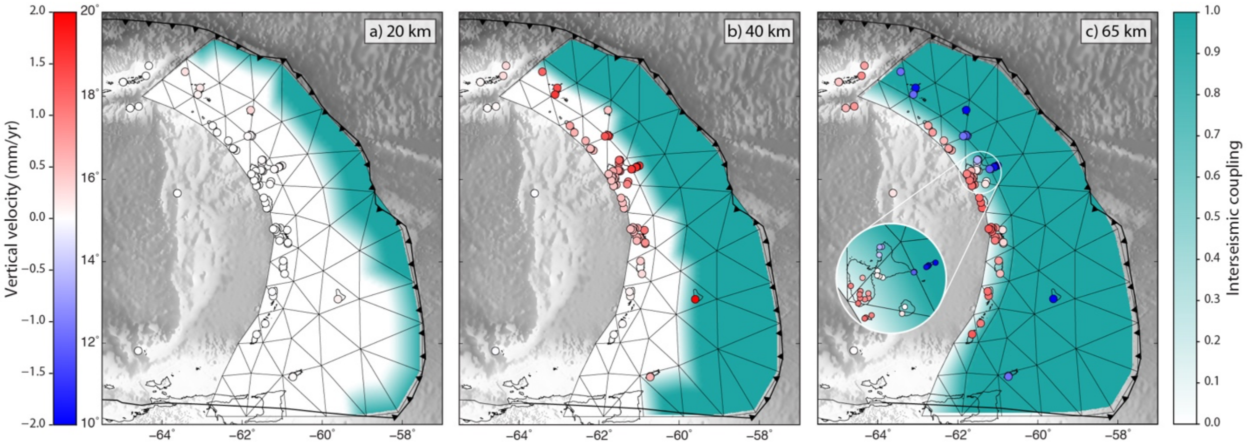

Figure 3. Predicted vertical motions for three scenarios of interseismic coupling: a downdip locking limit of 20 km (a), 40 km (b), and 65 km (c). The inset in C shows the transition from predicted subsidence to uplift from NE to SW for the Guadeloupe Archipelago. Figure S2 shows these models with partial (i.e., 50%) instead of full locking for these three depth ranges.

3. Long-term Subsidence Along the Entire Margin

The comparison of subsidence in the Lesser Antilles over a range of time scales shows a long-term subsidence trend, though the rate derived from reef terraces over 125 kyr is smaller than the more recent observations from micro-atolls and GNSS (i.e., < 0.5 mm/yr vs. 1-2 mm/yr, respectively; Fig. 4). Although within uncertainties, this difference could indicate an increase in the overall subsidence rate since the last hundreds of thousands of years, as suggested by Leclerc and Feuillet (2019). Variations in long-term subsidence rates have been observed in the geological record as well (e.g., Cornée et al., 2021) and may result from time-dependent variations of the incoming slab properties (e.g., in terms of roughness or buoyancy). Another hypothesis to explain the short- vs. long-term difference is that the current short-term subsidence rate represents a snapshot in time, while longer-term estimates average out variations in subsidence rate on short time scales and may thus appear lower. This would assume that, over time intervals others than the Present-day, subsidence rate was lower than at present.

As the general subsidence of the Lesser Antilles cannot be attributed to interseismic locking of the subduction megathrust, one must consider that longer-term processes are at play. For instance, crustal faulting and volcano-related deformation (e.g., magmatic chamber cooling or loading of volcanic edifices) may contribute to the overall subsidence, although it is unlikely that these processes explain the 1-2 mm/yr subsidence that would affect the entire arc. Variations in vertical motion between islands could be attributed to either intra-arc crustal faulting (Feuillet et al., 2011) or to the subduction of oceanic ridges that may temporarily and locally affect vertical motion of the arc. This may be the case for La Désirade (a small island part of the Guadeloupe Archipelago; Fig. 1) that has undergone substantial uplift starting in the Calabrian (~1.48 Ma), followed by a decrease to negligible rates since 122 ka, possibly due to the transient influence of the subducting Tiburon ridge (Fig. 4; Léticée et al., 2019). Although such local processes may contribute to the overall subsidence pattern, the subsidence signal we observe affects the entire arc and is thus best explained by a regional process rather than by the sum of local phenomena.

To understand the apparent long-term, margin-wide subsidence of the Lesser Antilles, we now consider the geodynamic and tectonic context of the region. Since the late Eocene (~38 Ma), two main extensional phases affected the Northern Lesser Antilles (NLA), 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 subsidence in the NLA forearc and the intra-arc Kalinago basin (0.34 mm/yr; Boucard et al., 2021, Cornée et al., 2021), as well as subsidence in the central part of the arc (offshore Guadeloupe; De Min et al., 2015). Recent estimates of NW-SE extension based on polygonal fault orientations indicate that the NLA back-arc is submitted to similar processes as the arc and forearc (Gay et al., 2021). Estimates of back-arc extension show a change from EW to SSE-NNW towards the south, while post-mid-Miocene subsidence is observed there as well, with increasing rates towards the southernmost part of the margin since Late Miocene (i.e., 0.02-0.12 mm/yr; Garrocq et al., 2021). While it remains difficult to reconcile some of these kinematic differences between the northern- and southern Lesser Antilles, tectonic subsidence for the more recent times (Fig. 4), including the present, is consistent with the post-mid-Miocene extension documented geologically and could be its on-going continuation.

In terms of processes, Boucard et al. (2021) argue that tectonic erosion is responsible for the forearc subsidence, as well as for the westward migration of the NLA arc in the early Miocene. Assuming such a mechanism could play a role in the north, where the incoming plate is relatively rough, the 7-km-thick pile of trench sediments in the south would likely overcome any material lost by tectonic erosion (De Min et al., 2015). This contrast in incoming plate properties may result in along-arc variability of the subsidence rate, though we do not observe this in the GNSS data. This signal may simply be hidden in the noise of the GNSS-derived vertical velocities. Alternately, an independent process, which remains to be identified, may be responsible for the subsidence in the south, producing similar rates as in the north. We argue that it is more likely that a larger-scale process is responsible for the margin-wide subsidence, while other processes such as tectonic erosion or intra-arc faulting may also be acting at a local scale. Here we propose that both the observed trench-perpendicular extension and the ongoing margin-wide subsidence are controlled by slab dynamics, possibly driven by slab rollback.

The Lesser Antilles subduction zone experienced eastward slab rollback and subsequent arc migration since ~59 Ma, while the latest migration of the volcanic arc occurred westward (e.g., Allen et al., 2019). Folding of the slab at depth, when it reaches the mantle transition zone, could produce episodic trench migration, with phases of retreat and advance (e.g., Schellart et al., 2007). Changes in slab buoyancy could tune such migration as well, for example when a sharp transition in ocean-floor age subducts, causing a temporary change in slab pull. A decrease in slab pull due to such a buoyancy change has been proposed for the westward jump of the volcanic arc in the Lesser Antilles (Braszus et al., 2021). The trench-perpendicular extension and margin-wide subsidence that have been observed since mid-Miocene may indicate that the Lesser Antilles subduction is currently progressing towards a stage of trench retreat again. Slab dynamic processes could also be responsible for the aseismic character of the subduction megathrust by tuning the subduction interface stress state, with an overall reduction in normal stress (Beall et al., 2021).

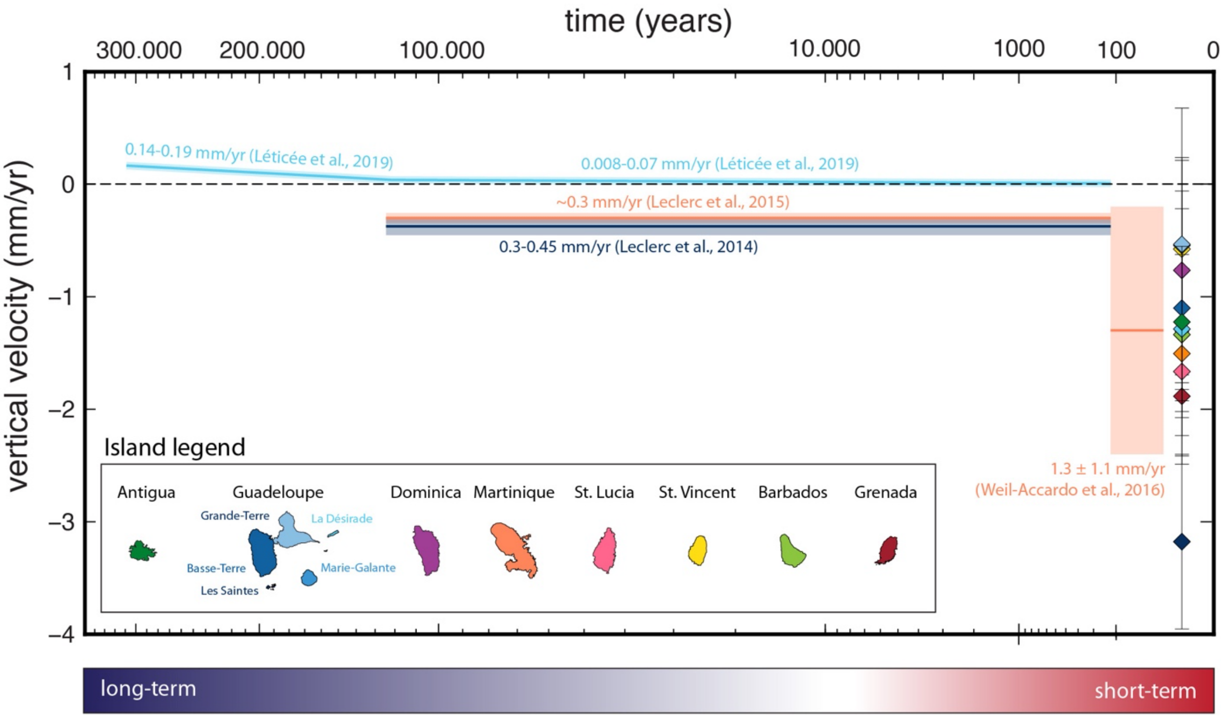

Figure 4. Overview of vertical tectonic motions on different time-scales, ranging from several tens of years (right) to hundreds of thousands of years (left) and color-coded per island. Diamond symbols indicate the weighted average velocities for all islands (modern geodesy; this study), while lines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

4. Implications for other subduction zones

In this work we show that present-day, margin-wide subsidence of the Lesser Antilles arc does not result from earthquake cycle deformation, but is probably part of the ongoing extension and related subsidence observed over geological timescales (10^4 to 10^6 years). The low interseismic coupling of the subduction interface makes the region unique as it allows us to observe longer-term and permanent deformation patterns that would otherwise be partially masked by elastic deformation related to the build-up and release of stresses along the megathrust (e.g., Menant et al., 2020). Several studies have shown how short-term deformation is partly converted into permanent strain, often related to uplift in the forearc as observed in Chile, for instance (Mouslopoulou et al., 2016; Jolivet et al., 2020). Our work suggests that interseismic strain does not need to be the main driver of such permanent deformation, and that in the Lesser Antilles, other, underlying processes related to subduction dynamics must be involved. Along the South American margin, Martinod et al. (2016) explain periods of forearc subsidence and uplift by an increase or decrease in convergence velocity, respectively. Regalla et al. (2013) find a temporal correlation between forearc subsidence, upper plate extension and back-arc spreading in northeastern Japan during the Miocene. These processes are observed on a regional scale (> 500 km), suggesting that they are governed by processes operating at lithospheric scale (e.g., downward flexure of the slab due to changes in slab buoyancy) rather than by local processes such as basal tectonic erosion. Present-day observations of geodetic subsidence in the NE Japan forearc that cannot be explained by predictions from a backslip model have previously been interpreted as a result of tectonic erosion as well (e.g., Heki, 2004), but could also result from a change in slab dynamics.

Models of lithospheric-scale tectonic subsidence or uplift rates at subduction volcanic arcs involve overlapping processes that are not easy to entangle. For instance, Menant et al. (2020) use thermo-mechanical simulations to show that transient stripping of sediments at the base of the forearc crust can lead to alternating uplift/subsidence sequences with vertical rates reaching 0.5-1 mm/yr, values that are consistent with the observations reported here. This process may contribute to the arc-wide subsidence of the Lesser Antilles arc, but would likely act differently in the northern and southern parts of the subduction, where incoming sediment thickness differs significantly. Another mechanism may involve the long-term dynamics of the subducting slab reported in the Lesser Antilles (Allen et al., 2019), as analog and numerical models indeed show that this process affects surface topography. For instance, Chen et al. (2017) show that a depression forms during the slab sinking phase due to slab suction. Although this depression disappears during slab rollback, its development would involve discernable subsidence rates as its final depth is on the order of a fraction of the trench depth. Slab rollback models also show extension in the upper plate (e.g., Xue et al., 2021) leading to the formation of crustal-scale normal faults which may lead to discernable subsidence as well (e.g., Sternai et al., 2014). In that case, arc subsidence rates could show significant along-arc variations, which does not appear to be the case in the Lesser Antilles from the data set presented here. Slab rollback also comes with negative dynamic topography, with amplitudes that are comparable to observed topographic variations (~1000s of meters) in both numerical and analog models (e.g., Husson 2006; Xue et al., 2021). Finally, mantle flow at the scale of lithospheric plates may also contribute to long-term vertical motions of subduction arcs. For instance, Chen et al. (2021) show that the westward flow of mantle material from the Galapagos plume through the Panama subduction slab window underneath the Caribbean plate to induces a tilting of the Caribbean plate, resulting in 100s of meters of negative dynamic topography at the Lesser Antilles arc. Although dynamic topography models do not provide, to our knowledge, vertical motion rates that could be directly compared to our observations, the fact that they predict a signal comparable to observed long-term vertical deformation indicates that they also contribute to current vertical rates at subduction volcanic arcs.

Conclusions

Vertical velocities from continuously operating GNSS stations in the Lesser Antilles show a regional subsidence of the island arc at 1-2 mm/yr. Such short-term signal fits the longer-term pattern of geological subsidence observed since at least 125 ka, as well as data from coral microatolls from Martinique to Barbuda over the past ~100 years. We show that this subsidence, which extends beyond the islands of Martinique and Guadeloupe, is a margin-wide feature with similar rates in the north and south Lesser Antilles. Using elastic dislocation models, we show that a locked or partially-locked subduction interface would produce uplift of the island arc, opposite to the observations, hence supporting a poorly-coupled subduction. The recent (125 ka to Present) subsidence is consistent with the post-mid-Miocene extension documented geologically, though variations in rates may have occurred over time. That this subsidence concerns the entire arc, in spite of lateral variations of the properties of the subducting oceanic plate, suggests that it is controlled by long-term processes related to slab dynamics, such as slab rollback.

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Author Contribution Statement

E.M. van Rijsingen, E. Calais and R. Jolivet designed the study and contributed to the data analysis and interpretation of the results. E. Calais, J.-B de Chabalier, R. Robertson, G.A. Ryan and S. Symithe have contributed to data collection and processing. All authors contributed to the manuscript.

Data Availability Statement

This work uses data services provided by the UNAVCO Facility with support from the U.S. National Science Foundation (NSF) and National Aeronautics and Space Administration (NASA) under NSF Cooperative Agreement EAR-0735156. Permanent and episodic GNSS within the OVSG, OVSM, and SRC footprint in the Lesser Antilles have been funded by CNRS-INSU-ACI programs originally, then through three FEDER European Community programs (CPER-PO and Interreg IV and V Caraïbe projects) cofunded by the French Ministry of Research, the French Ministry of Environment, the Guadeloupe Regional Council, and the IPGP. The vertical GNSS velocities presented in this work are included in the supporting information; data are also openly available from the IGS (http://www.igs.org/), UNAVCO (www.unavco.org), and IPGP data center (http://volobsis.ipgp.fr/) archives.

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