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Abstract

The Eocene tectonic evolution of the easternmost Caribbean Plate (CP) boundary, *i.e.* the Lesser Antilles subduction zone (LASZ), is debated. Recents works shed light on a peculiar period of tectonic duality in the arc/back-arc regions. A compressive-to-transpressive regime occurred in the north, while rifting and seafloor spreading occurred in Grenada basin to the south. The mechanism for this strong spatial variation and its evolution through time has yet to be established. Here, using 3-D subduction mechanical models, we evaluate whether the change in the trench-curvature radius at the northeast corner of the CP could have modulated the duality. We assume asymmetrical CP boundaries at the north (from east to west: oblique subduction to strike-slip) and at the south (subduction-transform edge propagator-like behavior). Regardless of the imposed trench curvature, the southern half of our modeled CP always undergoes a NW-to-W-oriented extension due to the tendency of the southernmost part of the South-America slab to rollback. In contrast, the tectonic regime in the northeast corner of the CP depends on the trench-curvature radius. A low radius promotes transtension-to-transpression, with a NE-oriented compressive component of the principal stress. A high trench-curvature largely reduces the compressive component and promotes an extensive regime similar to that in the south. We thus propose that an initially low-curvature radius of the NE-LASZ triggered the tectonic N-S duality in the Eocene and led to an ephemeral period of transpression/compression at the north, although an additional mechanism might have been required to locally enhance compression.

1 Introduction

The Lesser Antilles subduction zone (hereafter LASZ), at the easternmost boundary of the narrow Caribbean plate is one of the most arcuate active subduction settings (Fig. 1a). The subducting plate of the LASZ consists of both the North and South American plates, hereafter collectively referred to as the American plates, since their relative motion in the study area is negligeable. To the north, the convergence between the American and the Caribbean plates is highly oblique (ten Brink & Lin, 2004; Legendre et al., 2018; Laurencin et al., 2019) and evolves to pure strike-slip motion in western Hispaniola and South Cuba (Calais et al., 2002; Mann et al., 2002; Rodriguez-Zurrunero et al., 2020), where a transform fault-system connects the plate boundary to the Cayman Trough (Leroy et al., 2000). At the south, the plate boundary is predominantly strike-slip and formed by a Subduction-Transform Edge Propagator (STEP) fault (Govers & Wortel, 2005) in as much as the subducting plate tears as it subducts (VanDecard et al. 2003, Clark et al 2008; Padron et al. 2020). Both the north and the south strike-slip plate boundaries as well as the shape of the subduction trench have been mostly acquired during the Eocene (Pindell and Kennan, 2009; Escalonna and Mann 2011; Philippon et al., 2020b).

Intriguingly, major tectonic events are thought to have occurred during the Eocene which caused the rise and the demise of a regional land bridge in the arc or back-arc areas (Iturralde-Vinent and MacPhee, 1999) and allowed the dispersal of terrestrial fauna from South America to the Greater Antilles (e.g. Marivaux et al., 2020). The spatio-temporal variations of the tectonic forcing that may have connected the geodynamical and biological evolutions in the Caribbean remain nonetheless fundamentally unknown. Recent studies have illuminated a period of compression and shortening in the arc/back-arc of the Northern Lesser Antilles which may partly explain a regional uplift in the middle to late Eocene (emersion of the GraNoLA land, (Philippon et al., 2020a)). In the island of Puerto Rico a transpressive tectonic regime has also been recorded in the Eocene (Lao-Davila et al., 2014). Though, while compression/transpression occurred in the northern arc/back-area, the southern part underwent stretching and spreading in the early and middle Eocene, respectively (Bouysse et al., 1988; Garrocq et al., 2021). Hereafter, we refer to this peculiar distribution of stress field to as the Eocene-tectonic duality of the LASZ. This episode of latitudinal variation ended in the late Eocene and may have coincided with or preceded trench bending at the northern LASZ.

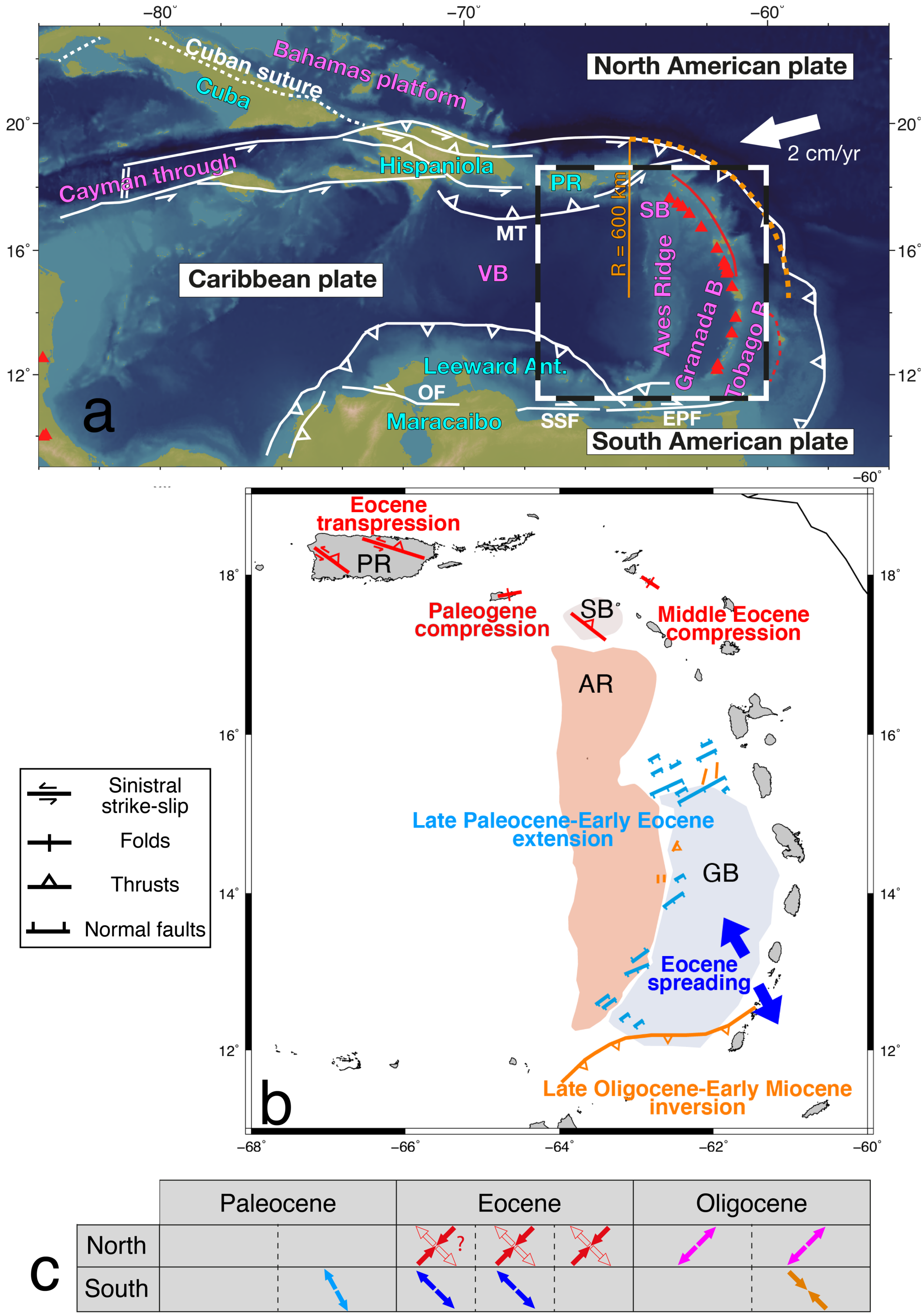

Figure 1 *: a) Map of the Caribbean region with active plate boundaries and major faults. The region of highlighted at the east. b) Reported main faulting systems indicating the tectonic regime of the Caribbean plate at various times during the Paleogene. MT: Muertos trough;VB: Venezuela Basin; SB: Saba Bank; AR: Aves Ridge; GB: Grenada basin. OF: Oca fault; PR: Puerto Rico; SSF: San Sebastian fault; EPF: El Pilar fault. c) Table illustrating the tectonic duality in the arc/back-arc region of the LASZ. The arrow colors correspond to that of the structures in panel b) with the exception of the Oligocene inversion (magenta) observed in the Saba bank and St. Barth (*Philippon et al., 2020a) *but not reported in the map.*

Understanding the spatial distribution of deformation in the arc and back-arc of the LASZ during the Eocene is a crucial first step for exploring the plausibility and extent of land emersions. The present contribution aims to more specifically decipher whether the acquisition of the trench curvature, combined with a northern subduction-to-strike slip boundary and a southern free subduction boundary (STEP fault) during the Eocene could have provoked a strong variation of the state of stress from north to south at the easternmost Caribbean plate (Fig. 1b).

The three-dimensional shape of the subduction trench and the convergence obliquity have been shown to impact the distribution of stresses in the overriding plate. Bonnardot et al. (2008b) showed that symmetric sea-wards (subducting-plate-wards) concave and convex margins lead to trench-parallel extension and compression, respectively, in the forearc/arc area near the apex of the curvature. That is because the direction of non-hydrostatic forces at the subduction interface either diverge from or converge to that area of the forearc in concave and convex settings, respectively. Furthermore, shear stresses along the subduction interface induce shear parallel to the trench in the forearc region where the convergence is the most oblique, for instance at both sides of a symmetrical curved margin (Boutelier et al., 2010). Obliquity can further lead to strain partitioning and to localization of shear in pre-weakened areas such as the arc region (Chemenda et al., 2000). In nature, these 3-d effects may have affected regions of arcuate subduction trenches such as the Bolivian orocline (Boutelier et al., 2010) or the western Aleutians (Ryan and Scholl, 1989). In the Northern Lesser Antilles, Paleogene V-shaped basins in the forearc may have resulted from the bending of the trench and development of a convex subduction setting which favored regional-scale block rotations (Laurencin et al., 2017; Boucard et al., 2021). The basins developed under the influence of a strong convergence obliquity along a highly curved trench which promoted trench-parallel forearc extension since at least the end of the Oligocene (e.g. Feuillet et al. 2002; Boucard et al., 2021). It is plausible that a temporal variation in trench bending and subsequent convergence obliquity during the Eocene have also affected the spatio-temporal evolution of the stress field in the arc/back-arc region of the LASZ, but their impact remains yet to be quantified.

Here, by using mechanical subduction models, we show that a low trench-curvature radius could have promoted a tectonic duality in the LASZ from early to mid- Eocene, favoring a transpressive event in the northern arc/back-arc area. An increasing curvature radius from the middle-to-late Eocene may have assisted a release of stresses in the same region. Below, we first describe the geodynamical environment of the LASZ during the Paleogene, focusing on Eocene times. Then, we describe the numerical approach that we undertake before presenting our modeling results and their implication for the regional tectonic evolution.

2 Tectonic Setting

The integrated story of the Caribbean plate and associated subduction zones has been the matter of various tectonic reconstructions (e.g., Meschede and Frisch, 1998; James 2009; Pindell and Kennan, 2009; Boschman et al., 2014). The onset of westward subduction at the north-eastern boundary of the Caribbean plate occurred in the Cretaceous, probably not later than 90 Ma (Pindell & Kennan, 2009; Mann, 2007). Until the late Paleocene the Caribbean plate hosted a volcanic arc which spanned the width of the plate, called the Great Arc of the Caribbean (GAC) (Burke et al., 1978). This former arc was associated with the SW-dipping subduction of a proto-Caribbean seafloor and was contemporaneous of a NE-SW relative convergence between the Caribbean plate and the Americas. From the end of the Paleocene to the early Eocene, the volcanic activity of the GAC ceased (Fig. 2a). At the easternmost part of the Caribbean plate, corresponding today to the LASZ, the volcanic front migrated eastwards from the Aves ridge to the Lesser Antilles arc between the early and the middle Eocene (Fig. 2b).. The relative convergence between the Caribbean and the American plates switched to E-W. This plate reorganization was accompanied by major tectonic events in Paleocene and Eocene times, which we highlight below. Our brief description follows a geographic path from North to South.

From the Paleocene to the early Eocene, the northern segment of the GAC, presently corresponding to western and central Cuba, collided with the buoyant Bahamas platform forming an orogenic belt (Iturralde-Vinent et al., 1994; Garcia-Casco et al., 2008; Cruz-Orosa et al., 2012) (Fig. 2a). Thrusting of the Cuban terranes onto the Bahamas platform was achieved by early middle-Eocene and led to the formation of the Cuban suture zone (Bralower and Iturralde-Vinent, 1997; Stanek et al., 2009). During the frontal arc-Bahamas collision, the direction of compression in Central Cuba was reported to pass from a SSW-NNE orientation before the early Eocene, to an oblique compression SW-NE in middle-Eocene and to WSW-ENE after Mid-Eocene (Cruz-Orosa et al., 2012), thereby suggesting a possible tectonic reorganization during the early Eocene.

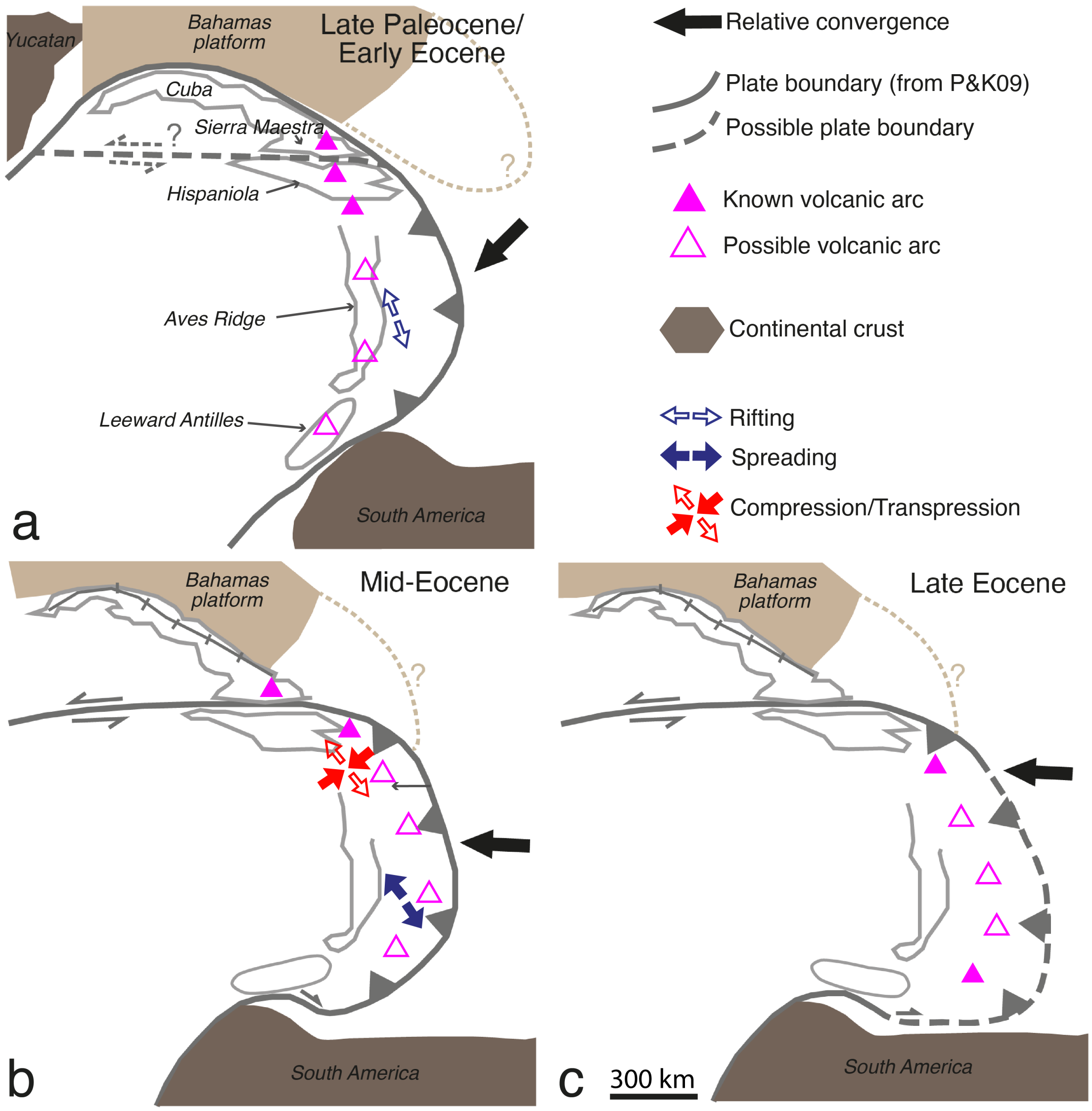

Figure 2 *: Illustrative cartoon of the evolution of the tectonic setting of the Caribbean. The stages at the late Paleocene and Mid-Eocene are modified from Pindell & Kennan, [2009]. We have also sketched a possible extension of the Bahamas platform following e.g. Lao-Davila et al., 2014. The stage at the late Eocene is modified from the Mid-Eocene reconstruction in Pindell & Kennan 2009 by adding an assumption on the southern trench evolution following spreading in the Grenada basin.*

The collision ultimately caused the jump of the Caribbean-North America plate boundary towards an E-W transform system south of Cuba (Fig. 2a). South of the Sierra Maestra, the strike-slip motion was accommodated by the opening of the Cayman Through from ~50-49 Ma (Rosencrantz 1988; Leroy et al., 2000). Prior to the spreading, a period of extensional rifting (pull apart basin) may have started as early as the late Paleocene (Pubellier et al., 2000). Rosencrantz et al., (1990) proposed that the E-W strike-slip motion between the plates was coeval with the thrusting of Cuba onto the Bahamas platform, and thus may have started as early as the late Paleocene-early Eocene. As shown below, this is consistent with the geological record in Hispaniola which does not display substantial compressive tectonics at that time, as it would be expected given the reconstructed position of the island facing a possible thrust of the SE end of the Bahamas platform (Fig 2b).

Hispaniola records some pieces of evidence of compressive tectonics in the Eocene but most of the contractional structures (folds and thrusts) formed after the middle-Eocene (Heubeck et al., 1991; Pubellier et al., 2000; Huerta et al., 2002). Furthermore, recent geophysical imaging of the crust in western Hispaniola only suggests modest shortening (post-Cretaceous and pre-Neogene) across the Trans-Haitian belt (Corbeau et al., 2017). The lack of evidence of a major compressive event in Hispaniola during the Eocene may indicate that the collision with the Bahamas platform, if it occurred at that time, played only a minor effect on the regional tectonics or that it was mostly accommodated by a sinistral strike-slip motion. Our model setup presented below is based on such an assumption that the northernmost segment of the Caribbean plate was not a collisional front anymore by the early Eocene and was instead an oblique subduction-to-transform plate boundary, similar to the present-day configuration (Rodriguez-Zurrunero et al., 2020).

The position of Puerto Rico relative to Hispaniola was south or southeast in the early to mid-Eocene (Jolly et al., 1998; Pindell & Kennan 2009). A volcanic activity of Eocene age with a geochemical signature of extensional setting has also been reported in the southeast of Puerto Rico (Schellekens, 1991). The northeastern part of the island records a volcanic activity up to the mid-Eocene (Jolly et al.,1998). Several lines of evidence support a transpressive (NE-SW) tectonic regime there across the Eocene (Fig. 1b). This regime has been recorded principally in the Southern Puerto Rico Fault Zone and the Northern Puerto Rico Fault Zone where transpression was accommodated by fold-and-thrusts belts and conjugate sinistral strike-slip faults (Lao-Davila, 2012; 2014). It was active from the middle-Eocene to the early-Oligocene, although it may have started before (Lao-Davila et al., 2014; Roman et al., 2020). Furthermore, the transpressive/compressive regime may have been accommodated in the rear-back arc through the formation of the east-west trending Muertos trough and the overlying Muertos fold-and-thrust belt (Granja-Buña et al., 2009; 2014) which extends from southeast of Puerto Rico to the south of Central Hispaniola. Note that a compressive event of Paleogene age was also reported in the Virgin Islands (St Croix) (Speed, 1989).

Further east (or southeast), in the vicinity of the Saba bank, combined onshore and offshore geological and geophysical analysis illuminated a period of compressive regime which inverted pre-middle Eocene normal faults offshore in the region of the Saba Bank and lead to contractional folding on the island of St Barthélemy dated between at least ~42.5 Ma and up to ~39.7 Ma (Philippon et al., 2020a). Put together, the above observations constraian a period of compression and/or transpression during at least part of the Eocene which affected a relatively large area of the northeastern corner of the Caribbean plate (red domain, Fig. 2b).

In the central and southern part of the LASZ, the GAC occupied the present-day Aves Ridge bathymetric feature and was active until c.a. 59 Ma (Fox et al., 1971; Neill et al., 2011; Wright & Wyld, 2011). The opening of the Grenada basin in the southern half of the plate was contemporaneous or followed an east-wards arc migration (Bouysse et al., 1988; Pindell and Barret 1990; Allen et al., 2019; Garrocq et al., 2021). Garrocq et al., (2021) has proposed a three-stage shaping of the basin, including a NNW-SSE stretching episode during the late Paleocene-early Eocene, followed by a NW-SE oceanic spreading of at least 100 km which ended in the late-middle Eocene (Fig. 1c).

Based on the recent data on both the compressive regime at the NE corner of the Caribbean plate and the extensive tectonics in the region corresponding to the Grenada basin, the North-South tectonic duality of the LASZ lasted from the early Eocene to the late Eocene, thus for a duration of 10 to 20 Myr.

From the early Paleocene onwards, the southern boundary of the Caribbean plate was mainly characterized by an oblique arc-continent collision between the extinct southern-end of the GAC and South America (Pindell and Barrett, 1990; Wright & Wyld, 2011). From the Paleocene to the early-middle Eocene, the Leeward Antilles collided obliquely with the northern Colombian margin northwest of the Maracaibo basin (Escalona and Mann 2011; Montes et al., 2019). Behind the collision front, a dextral strike-slip system to the north of the colliding extinct arc accommodated the regional transpressive regime (Beardsley

& Ave Lallemant, 2007). A net strike-slip motion involving the Oca-San Sebastian-El Pilar fault system as a part of a STEP fault may have only started in the late Eocene-early Oligocene (Escalona and Mann 2011). However, in our modeling approach, we make the simplification of a STEP fault-like boundary existing at the southern boundary of the Caribbean plate from the early Eocene, similar to the configuration in the mid-Eocene Reconstruction of Pindell & Kennan (2009) (Fig. 2b).

3 Modeling approach

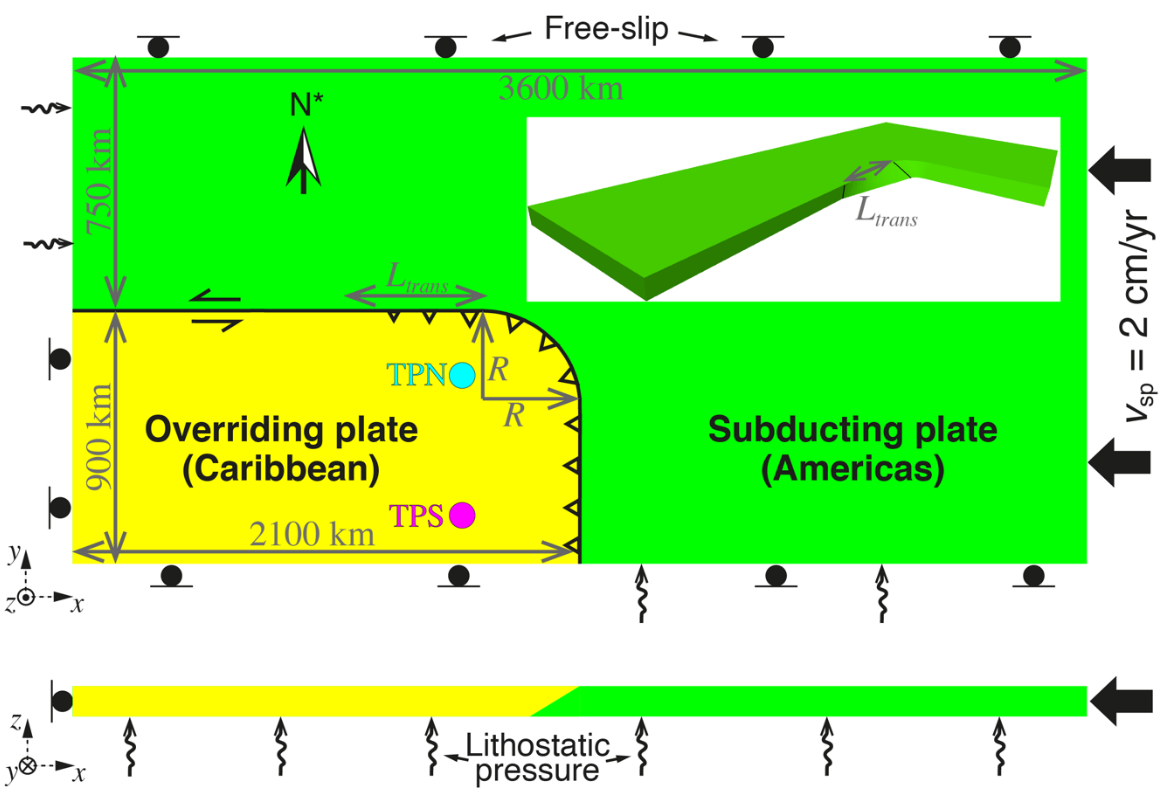

***Figure 3**: Initial model setup as seen from a "top-view" (top figure) and a "lateral view" (bottom), with all boundary conditions. An idealized north (N*) points in the same direction as the y-axis. Note that the southern boundary condition of the subducting plate is set to free-slip until it enters the subduction trench, after what we apply only a lithostatic pressure to simulate a STEP-like plate boundary. The inset depicts a 3-d view of the subducting plate to show the transitional plate boundary. The northern (TPN) and the southern (TPS) tracking points are used to track the evolution of the principal stresses in the idealized arc to back-arc regions.*

To address the tectonic evolution of the LASZ during the Eocene, we perform mechanical models of subduction using the three-dimensional version of the code ADELI (Hassani et al., 1997) which is suitable for studying the effect of the trench curvature on the state of stresses of the overriding plate. In our approach (see governing equations in Appendix), the lithospheric plates are viscoelastic solids and the mantle is treated as an inviscid fluid (Hassani et al., 1997; Buiter, 2001; Gibert et al., 2012). Models of subduction dynamics showed that an inviscid mantle produces results comparable to those that would be obtained with a mantle of low viscous resistance (viscosity lower than 10^{20} Pa s), if the plates were sufficiently strong (viscosity ratios of about 10^4) (Bonnardot et al., 2008; Cerpa et al., 2014).

Our models consist of two 80-km thick homogeneous lithospheric plates initially separated by a planar fault (Fig. 3). The viscosity of the plates is 10^{24} Pa s and their density exceeds that of the mantle by 50 kg m^{-3}. Therefore, the subducting plate has roughly the average characteristics of a 70-Ma old lithosphere. The friction at the contact fault is set to a relatively low value of 0.01. The Young modulus and Poisson's ratio are set values of 10^{11} Pa and 0.25, respectively.

The overriding plate (Caribbean Plate – CP) is 900-km wide, which approximately corresponds to the present-day width. It is fixed at its trailing edge given that the CP has been roughly immobile in an absolute reference since at least 50 Ma (Boschman et al., 2014). The velocity of the 1650-km wide (2400-km long) subducting plate (American plate - AP) is imposed at its trailing edge (Fig. 3). The latter assumption is based on the fact that the motion of the Americas was probably controlled by the eastward-dipping subductions occurring at their western boundary since at least the Cretaceous (Ramos 2009; Sigloch and Mihalynuk 2013) and perhaps by a regional mantle circulation (e.g. Faccenna et al., 2017), which must thus have controlled the velocity of the subducting plate in the LASZ. We impose the present-day value (2 cm/yr) to the velocity of the AP, and thus neglect the potential transient effects induced by variations in kinematics (Cerpa et al., 2018; Cerpa and Arcay 2020). The lateral edges of the AP are free to slip. Note that the southernmost lateral edge of the AP is let free when it plunges into the inviscid mantle, approximating thus a STEP fault.

The initial in-plane radius of curvature of the NE trench is set a value R (Fig. 3). This is one of the most important parameters of our models. However, it is little constrained at Eocene times. We hypothesize that an increase in trench-curvature radius is a plausible scenario after the jump of the Caribbean-North

America plate boundary. After the jump, the new plate boundary system was indeed partly created by a cut in the former CP by a transform fault that linked the Cayman rift/spreading axis to the subduction trench in the east (Pindell and Barrett, 1990; Boucard et al., 2021). By that time, the latter plate boundary may have been more rectilinear than at present-day (Fig. 2). We nonetheless acknowledge that the reported evidence of trench bending at the NE corner of the Caribbean plate pointed out a post-late Eocene deformation. This includes a post-Eocene 45˚ counter-clockwise rotation of Puerto Rico (van Fossen 1989), and a post-Oligocene 15-20˚ counter-clockwise rotation of the St Barthelemy island (Philippon et al., 2020b) associated with a more pervasive deeply-rooting NE-SW fracturing, which fragmented the arc–forearc into a set of shallow spurs and deep valleys (Laurencin, et al., 2017; Boucard et al., 2021). Yet, it remains uncertain whether the bending of the trench would have been accommodated through block rotations or, instead, by a more diffuse deformational pattern, especially in regions weakened by active arc volcanism (Saba Bank, Puerto-Rico). In what follows, we explore two end-members for the trench-curvature in the models: an arbitrary low radius of 200 km and a relatively high radius of 600 km equivalent to the present-day apparent curvature of the LASZ (Fig. 1).

Initially, the westward termination of the subduction plane (30˚ dip), that is the termination of the curved trench, is at a distance L_{trans} from the eastward termination of the vertical (90˚ dip) transform fault (Fig. 3 inset). In between these two points the dip-angle of the contact fault between the two plates increases westwards. This transitional interplate plane is hereafter referred to as the transitional plate boundary. Note that during the evolution of the model, the transitional plate boundary tends to extend westwards owing to the displacement of the westernmost termination of the vertical fault on the subducting plate side, while the easternmost termination of the transitional plate boundary on the overriding plate side tends to be stationary. As seen below, such a displacement as well as the imposed initial value of L_{trans} can affect the modeled state of stress, mostly in the interior of the overriding plate. Since the value of L_{trans} in nature cannot be constrained otherwise than qualitatively, we explore several values.

Finally, the tectonic duality in the Eocene is mostly inferred from tectono-sedimentary observations at the surface of the LASZ, mainly located in the arc and back-arc regions. We thus particularly focus on the modeled stress field at the surface of the CP at a distance from the trench relevant for an idealized arc/back-arc region. We particularly use two arbitrarily-defined point (hereafter referred to as the tracking points), which lie at an initial distance of 300 km from the eastern trench. Furthermore, the Tracking Point at North

(TPN) and at South (TPS) are initially placed at a distance of 200 km from the north and south CP boundary, respectively (Fig. 3).

4 Modeling results

4.1 Reference model

We first consider a reference model where the trench-curvature radius is relatively low ($R = 200$ km, Fig. 4). The length of the transitional plate boundary is L_{trans} = 700 km.

All models are characterized by an initiation phase where the convergence generates compression of the overriding plate (subduction initiation). During the subduction initiation (*i.e.* after ~18 Myr), the subducting plate plunges into the mantle with a penetration varying along the margin. At south, a "normal" subduction occurs, where the trench-normal convergence increases the length of the subducting slab with time. At the NE corner of the overriding plate, the convergence partitions between a sinking of the slab into the mantle and an E-W displacement of AP relative to CP. West of the transitional plate boundary, the relative motion between the two plates is purely strike-slip. As aforementioned, the westward termination of the transitional plate boundary moves westwards on the subducting plate side. Thus, the apparent length of the transitional plate boundary tends to increase with time.

At the model-time of $t = 21$ Myr (Fig 4a), the tip of the subducting slab in the southernmost part of the model reaches a depth of 430 km. The length of the slab in the southern part is sufficiently long (i.e. the slab pull is sufficiently high) to generate a quasi-trench normal traction on the overriding plate. We hereafter referred this force to as the trench-normal traction. The traction occurs because the slab-pull force is transmitted to the overriding plate as non-lithostatic forces acting on the subduction interface. The resulting tension at the surface of the overriding plate is illustrated by the principal stresses in regions lying at distances of more than 200 km and less than 500 km from the trench. There, we observe an extensive component of the principal stresses that is oriented NNW-SSE to NW-SE and rotates to W-E along the southern-free slip boundary. Thus, the extension points towards the southernmost part of the subduction trench where the trench-normal traction is the highest. The magnitude of the extension is about 100-150 MPa at a distance of 200-400 km away from the trench (arc/back-arc idealized region) as illustrated by the magnitude of extension at the southern-tracking point (TPS in Fig. 4c). The extension reaches locally 200 MPa close to the southern boundary. Note that a compressive component, with a relatively low magnitude (~50 MPa, Fig. 4c), is also observed in this southern-half of the CP. The magnitude of the second invariant of the deviatoric stresses (J2~300 MPa) along the southern boundary is controlled by both the trench-normal traction and the out-of-plane stress induced by flexure of the CP.

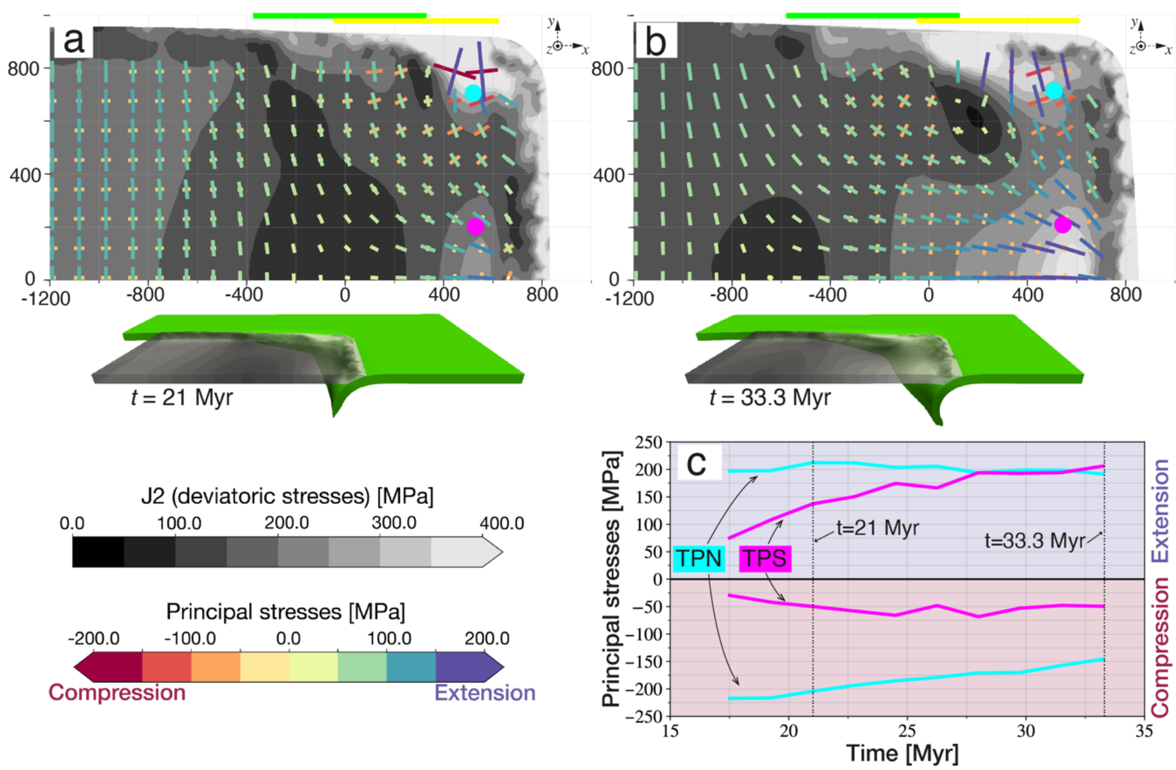

***Figure 4** : a-b) Snapshots of the time-evolution of the reference model with $R = 200$ km (a,b). The gray colorscale gives the second invariant of deviatoric stresses (J2) at the surface of the overriding plate using a top view. The lines give the direction of the in-plane principal stresses at the surface of the overriding plate, the intensity of which is given by both the red-to-blue colorscale and the segment length. Negative (redish) values are for compression and positive (bluish) values are for extension. Note that we only represent the principal stresses at distances of more than 100 km from the interplate boundary as we focus on the tectonic evolution of the ideal arc/back-arc region. The green and yellow rectangles above the panels indicate the horizontal extent (each rectangle has a length L_{trans}) of the geometric transitional plate boundary on both the subducting and the overriding plate sides, respectively. c) Evolution of the magnitude of the principal stresses at the two representative locations of the overriding plate tectonic regime: Tracking Point at North (TPN) in cyan and Tracking Point at South (TPS) in magenta. The point locations are also reported in the top view of the overriding plate.*

Near the NE corner of the CP, we observe a region of relatively high in-plane deviatoric stresses (J2 > 300 MPa). The high-stresses are located near the trench but reach locations as far as 300 km away from the interplate boundary, coinciding thus with the vicinity of the center of the curved margin. In this region, we observe principal stresses with both a NNW-SSE extensive component and an approximately WSW-ENE compressive component. At the TPN, the extensive and compressive components have magnitudes of 210 and 205 MPa (Fig. 4c) and highlight a quasi-transpressive tectonic regime in the NE corner. Moreover, this high-sheared region overlaps another patch of moderate shear (J2~200 MPa) situated along the trench at a horizontal position x≃-200 km, which is induced by the indentation effect of the transitional plate boundary, as described below.

Finally, far away from the eastern subduction trench (distance of more than about 1000 km), the deviatoric stresses at the surface of the southern half of the overriding plate are relatively low (J2 < 150 MPa) and the W-E subduction-induced extension vanishes. Instead, a modest N-S extension (magnitude of approximately 120 MPa) is visible inland in front of the transform fault.

At $t = 33.3$ Myr (Fig. 4b), the southernmost slab tip has reached 690 km depth. Because of the important trench-normal traction, the extensive stresses reach 200 to 250 MPa in the southern half of the arc/back-arc region at distances from the trench of 300 to 500 km. The point TPS displays an extensive component of 206 MPa (Fig. 4c). As in the preceding stage of the model, a patch of moderate-to-high deviatoric stresses (J2=250-350 MPa) is observed in the vicinity of the center of the curved margin, that is in the arc/back-arc region of the NE corner of the CP. There, we observe that the NNW-oriented extensive and the ENE-oriented compressive components of the principal stresses display magnitudes of 150-200 and 150-180 MPa, respectively. The tracking point TPN exhibits extensive and compressive components of 192 and 146 MPa, respectively. The ratio of compression to extension, in the NE-corner is 76% and the tectonic regime becomes thus transtensive.

At the northwest of the TPN a patch of very high stresses is visible close to the transitional plate boundary along the subducting plate side which now lies between $x \simeq -550$ km and $x \simeq 200$ km. The stresses are particularly high (J2 of more than 400 MPa) near the eastern end of the transitional plate boundary on the subducting plate side which is impeded to subduct, creating a local indenter acting on the subduction interface. These very high stresses remain nonetheless in a region situated at a distance of less 150 km from the interplate boundary, corresponding to the ideal forearc region. Furthermore, the indentation effect of the transitional plate boundary generates some compression (magnitude 50-70 MPa) oriented N-S to NNE-SSW in the rear-back arc region (area in the ranges $x = [-400; 0]$ km and $y = [0; 700]$ km), that is at distances of more than 800 from the eastern trench. Farther inland ($x < -400$ km) the compressive component vanishes.

To sum up, at the mature stages of the reference model, four areas of varying tectonic regime can be distinguished at the surface of the overriding plate:

1) a southern arc/back-arc region where the trench-normal traction induces WNW-oriented to NNW-oriented extension.
2) a NE corner under high deviatoric stresses. This area displays a transpressive to transtensive regime that is due to the curved margin, the obliquity of subduction and the limited slab length. Note that this area undergoes a WSW-ENE-oriented compressive component.
3) a rear-back arc region that undergoes trench normal traction and compression oriented N-S to NNE-SSW induced by an indentation effect of the transitional plate boundary.
4) Distal inland regions where the stresses vanish and undergo only a small N-S oriented extension.

4.2 Model with a higher trench-curvature radius

We now consider a model with a higher trench-curvature radius ($R = 600$ km, Fig. 5), equivalent to that of the present-day LASZ (Fig. 1a). The transitional plate boundary initially spans the spatial range $x = -400$ to 300 km, and thus has the same length as that in the reference model.

At $t = 21$ Myr (Fig. 5a), at south, the trench-normal traction generates a prominent (magnitude higher than 100 MPa) NW-oriented to E-oriented extension in the arc/back-arc region in the southern half of the CP. For instance, the point TPS display an extensive stress of 140 MPa. Unlike the reference model, the deviatoric stresses do not show a substantial increase in magnitude as we approach the NE corner, and the principal stresses display a little compressive component. At the point TPN the extensive and compressive components are 105 and 25 MPa, respectively. The region of the overriding plate that overlies the transitional plate boundary undergoes high-shear stresses, especially in the vicinity of its eastern-end. Yet, the high-stresses region is within the idealized forearc area (distance of less than approximately 150 km away from the interplate boundary).

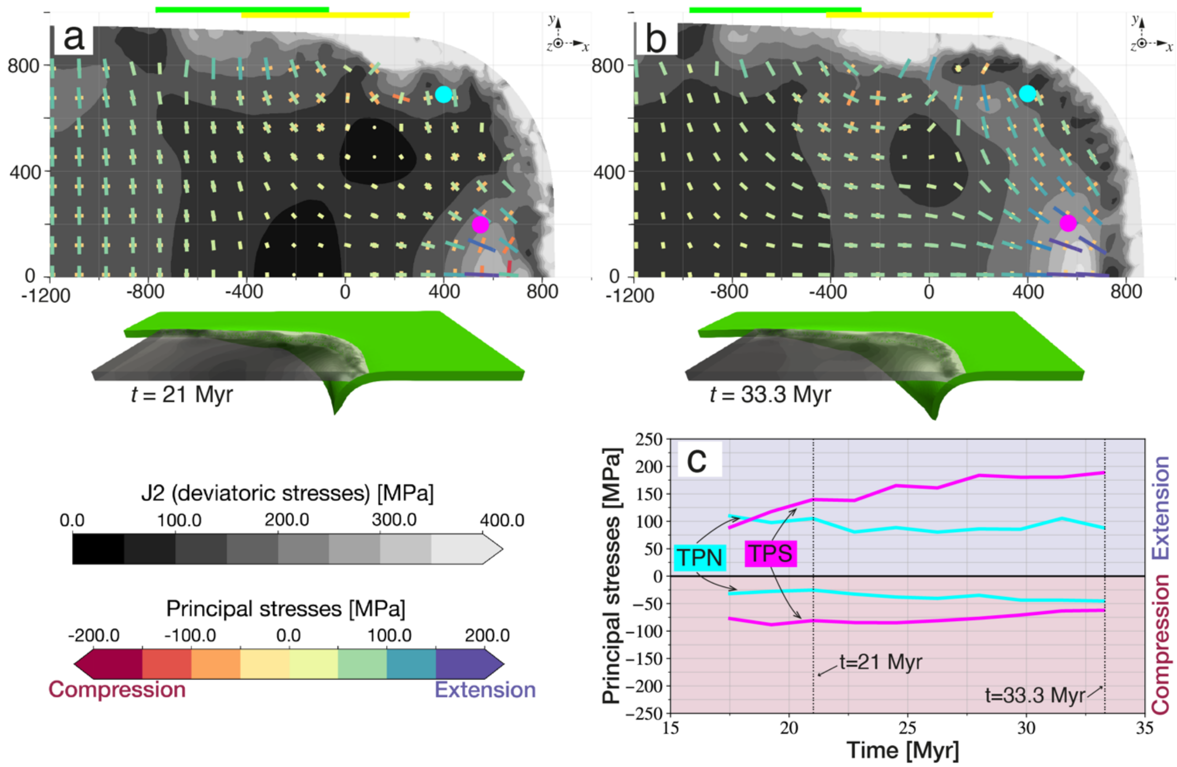

Figure 5 *: a-b) Snapshots of the time-evolution of the reference model with* $R = 600$ *km (a,b). c) Evolution of the magnitude of the principal stresses at the northern-tracking point (red) southern-tracking point (blue). The point locations are also reported in the top view of the overriding plate. For other legend details see caption of figure 4.*

At the model time $t = 33.3$ Myr, the southernmost tip of the subducting plate reaches a depth of ~690 km. The southern long trench-normal traction exerts a relatively strong tension on the overriding plate in the arc/back-arc region both in the north and in the south, as shown by the extensive component of the principal stresses (magnitude >100 MPa). Unlike the reference model, only modest stresses are observed at distances of more than 150 km from the trench in the NE corner of the CP. For instance, the point TPN displays a compressive component of 40 MPa, thus about 3 times lower that that observed in the reference model. The extension is moderately high at the same location, displaying a value of 105 MPa, thus only two times lower than that observed in the reference model. The ratio of compression to extension in the

N-E corner is approximately 40 % (in the reference model at the same stage the ratio is 76%), and highlight a transtensive regime.

It is important to note that in the model with $R = 600$ km, we do not observe substantial compression in the idealized arc/back-arc region of the NE corner. That is because, in the high-R model, the non-hydrostatic forces acting on the curved subduction interface converge towards a larger area compared to that in the reference model, thereby reducing the trench-normal compressive component. More generally, the maximum non-hydrostatic forces acting on the overriding plate of a convex-shaped margin are inversely proportional to the trench-curvature radius, as described by Bonnardot et al., [2008]. In contrast, the magnitude of the extensive component is controlled by the length of the southernmost subducting slab, and that is why we do not observe substantial differences between this model and the reference model.

Further north(west), the only patches of very high shear stresses are restricted to proximal region of the transitional plate boundary. As in the reference model, this part of the interplate boundary indents the idealized forearc, creating a NNE-oriented compressive component of the principal stresses. Yet, the latter reaches only a smaller area in the rear back-arc region (in the ranges $x = [-500; -100]$ km and $y = [400; 700]$ km) than in the reference model.

To summarize the mature stage (t=33.3 Myr) of the model with $R = 600$ km, we can identify four tectonic areas at the surface of the overriding plate:

1) a southern arc/back-arc region where the trench-normal traction induces WNW-oriented to NNW-oriented extension.
2) a NE arc/back-arc region under a transtensive/extensive regime with an extensive component of principal stresses orientated and rotating roughly similarly to that in the southern part. Note that the deviatoric stresses display only a moderate increase when approaching the NE corner, unlike the reference model.
3) a rear-back-arc region that undergoes trench normal traction and some compression induced by the transitional plate boundary in the northern half of the plate.
4) Distal inland regions where the stresses vanish and undergo only a small N-S oriented extension.

Three of these domains are very similar to the ones simulated with a lower radius of trench-curvature (R=200 km), i.e., areas 1, 3 and 4. The area 2 strongly differs from its equivalent obtained in the reference model with R=200 km, where the ratio of compression to extension is about two times higher, and tends towards a transpressive regime.

4.3 Model with a weaker overriding plate

We emphasize that in our modeled subduction setting, the trench-curvature radius plays an important role in the distribution of stresses at the surface of the OP. However, because in the two models presented above, the plates are relatively strong ($\eta = 10^{24}$ Pa s), the radius little evolves through time. We thus now run a model with the same initial trench-radius of curvature as in the reference model ($R = 200$ km) but with a weaker overriding plate (viscosity of 3×10^{23} Pa s) so that the trench is more able to bend. The overall evolution of the model with a weaker overriding plate is close to the one simulated in the reference model, except that because of its relative weakness the plate undergoes more deformation.

At $t = 24.8$ Myr, the compression that occurred at the initial stages of subduction has generated a greater shortening than in the reference model (Fig. 6a). The shortening is roughly homogeneous from North to South. At this mature stage of subduction, the southernmost slab tip has reached a depth of approximately 460 km. The slab rollback induces a NNW-oriented to W-oriented extension in the southern arc/back-arc region, as in the reference model at an equivalent stage (see Fig. 4a). The magnitude of the highest extensive principal stresses is nonetheless lower than simulated in the reference model. For instance, the extensive principal stress is 64 MPa at the TPS, whereas it reaches up to 200 MPa in the reference model at a similar location. Alike the reference model, a combination of in-plane extension and compression occurs near the NE-corner of the CP. The TPN displays magnitudes of the compressive and extensive principal stresses of 70 and 85 MPa, respectively, and thus denotes a quasi-transpressive. More generally, in the arc/back-arc area of the NE-corner, the orientation of the compressive component is E-W to ENE-WSW and its magnitude is up to 150 MPa at distance of more than 150 from the trench.

At the end of the model time ($t = 42.8$ Myr, Fig. 6b), the southern tip of the subducting slab has reached a depth of 690 km. By this time, the southernmost part of the CP has undergone more trenchward extension while the northernmost part has experienced more trenchward compression relative to that in the reference model where the horizontal deformation is negligible. Hence, in the model with a weaker plate, the apparent trench-radius of curvature tends to increase with time.

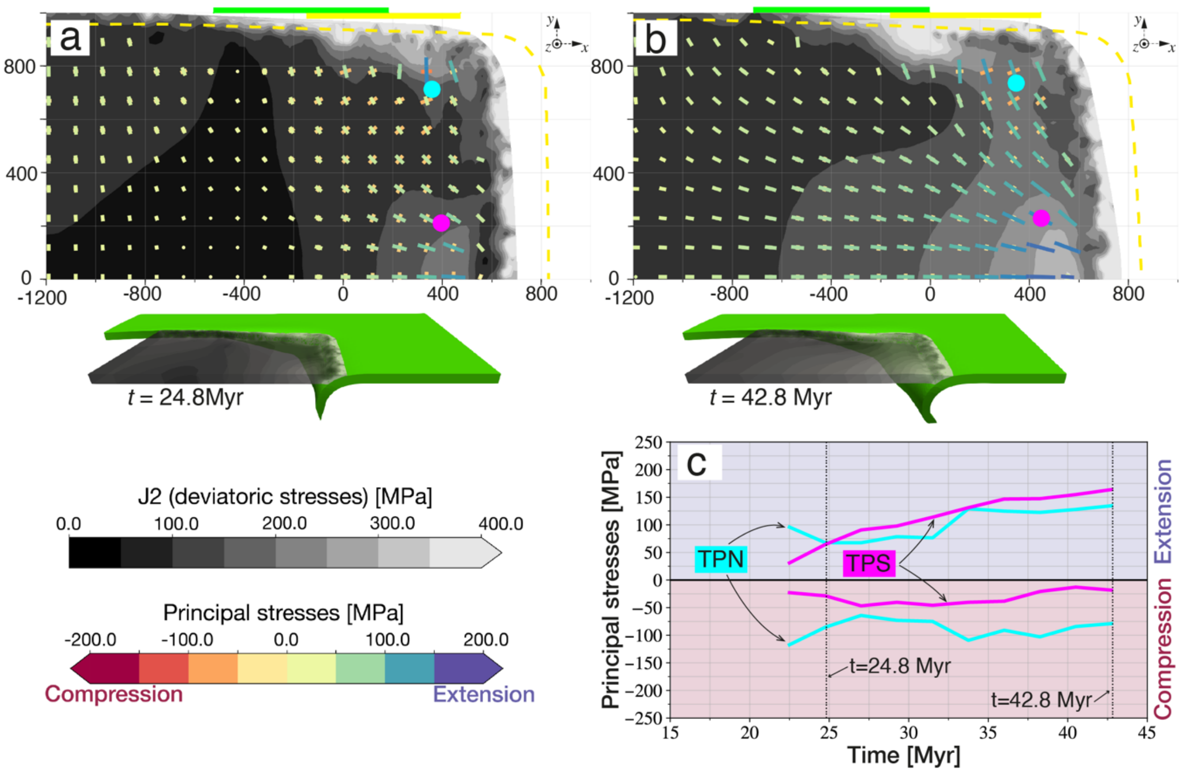

***Figure 6**: a-b) Snapshots of the time-evolution of the model performed with R=200 km and with a weaker overriding plate (*3×10^{23} *Pa s) than the reference model. The dashed yellow lines display the shape of the overriding plate in the reference model at equivalent stages of subduction (different times but with the same depth reached by the southernmost slab tip). See Figure 4 for other legend details.*

Interestingly, during the evolution of the model, we observe some decrease in the compressive component of the principal stresses while the extension builds up through time (see e.g. Fig. 6c). The latter occurs as the southern trench-normal traction increases while the apparent trench of curvature also tend to increase. At the TPS, the extensive and compressive stresses display values of 165 and 18 MPa respectively at t=42.9 Myr. At the TPN, these are 135 and 80 MPa with a ratio of compression to extension of approximately 60%. The latter value is thus intermediate between the tectonic regime in the reference model (~80%) and that in the model with a higher trench-curvature radius (~40%) for equivalent locations and at a similar stage of maturity of the subduction model.

We speculate that further trench bending could reduce the compressive component of the principal stresses at north, and thus establish a strong transpressive regime self-consistently. However, we cannot consider models with an extremely weak OP (viscosity $\leq 10^{23}$ Pa) because a too large deformation of the mesh cannot be handled without an appropriate remeshing technique which, in turn, might propagate numerical errors.

Furthermore, in nature, the southern stretching may have induced oceanic spreading (e.g. Garrocq et al., 2021) which may have then also participated to the evolution of the apparent trench of curvature. This effect is however not included in our models.

4.4 Models with various initial lengths of the transitional plate boundary

We have highlighted the effect of the transitional plate boundary on the state of stresses close to the boundary as well as in the rear-back arc. Because there is no accurate constraint on its length in nature for the Eocene, and because it might have changed through time, here, we explore models with different lengths. Two models are considered with values of L_{trans} lower (400 km; Fig. 7a,b) and higher (1150 km; Fig. 7c,d) than that of the reference model (700 km).

At the end of the simulations ($t = 33.3$ Myr – mature stage of subduction), the tectonic regime in the arc/back-arc region is equivalent in both models with $L_{trans} = 400$ km and $L_{trans} = 1150$ km. The southern part undergoes extension and the northern part undergoes transpression. The magnitude of the former is similar in both cases at the TPS which display a dominant extensive component of the principal stresses of about 210 MPa. The latter is equivalent in both models as they display a compression-to-extension ratio of 80% identical to that in the reference model, although the compressive component has a lower magnitude (130 MPa) in the model with $L_{trans} = 400$ km than that in the reference model (145 MPa) and that in the model with $L_{trans} = 1150$ km (150 MPa).

The two models exhibit moderate (J2>200 MPa) to very high deviatoric stresses (J2>400 MPa) along the transitional plate boundary. In particular, a patch of very high stresses is always located either close or east of the eastern-end of the transitional plate boundary (see green rectangles in Fig. 7a,c) but remains within a distances shorter than 100 km from the boundary. This high-stress area has a little influence on the tectonic regime in the NE corner which is controlled by the trench-curvature radius.

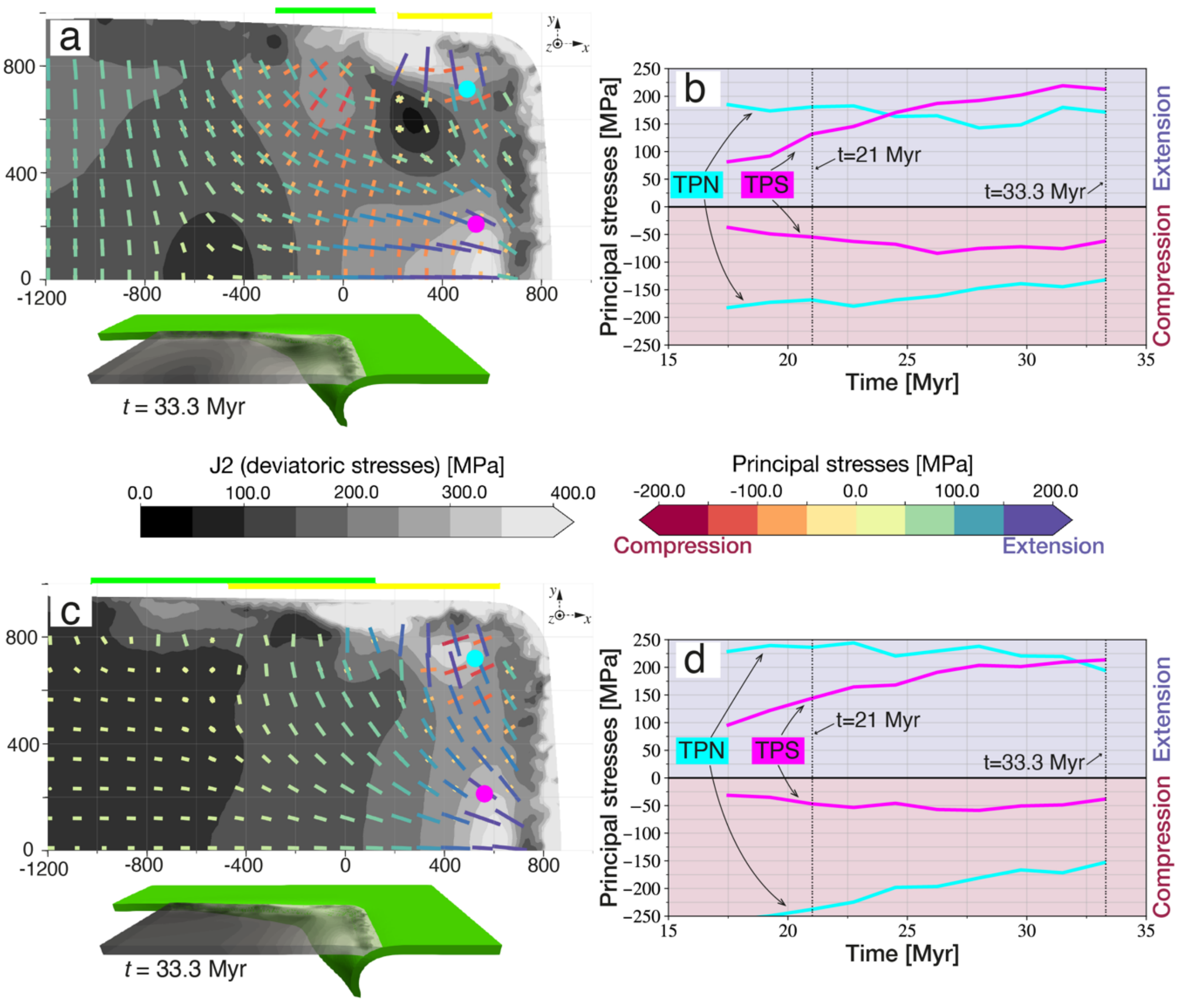

Figure 7: *Stress field at the end of the model time in the models with a lower ($L_{trans} = 400$ km ; a,b) and a higher ($L_{trans} = 1150$ km ; c,d) length of the transitional plate boundary than the reference model. See Figure 4 for other legend details.*

The major effect of changing the length of the transitional plate boundary is on the stress field in the rear-back arc area. The smallest value of L_{trans} induces a N-S to NE-SW oriented compressive component of moderate-to-high magnitude (80 to 120 MPa) in this area (roughly between $x = -400$ and 200 km) that faces the transitional plate boundary. We refer this effect to as an indenter-effect induced by the geometry of the transitional plate boundary which impedes subduction. The compression in the rear-back arc area remains however lower than in the arc/back-arc NE corner of the same model. In the model with the highest values of L_{trans}, the compressive component generated by the transitional plate boundary vanishes.

5. Discussion

5.1 Application to the tectonic duality during the Eocene

The main results presented above which are relevant for the comparison with the tectonic stress field in the LASZ during the Eocene are:

- In the context of an asymmetrical subduction zone bounded by a STEP fault at the south and a transition from subduction-to-strike slip at the north, the high trench-normal traction adjacent to the STEP-fault provokes extensional stresses at the surface of the overriding plate (oriented from NNW-SSE to W-E) in the southern portion of the margin at distances from the trench between 150 and beyond 400 km, thus ideally comprising the arc and back-arc regions.
- At the NE-trench corner, the trench curvature controls the obliquity of subduction. The obliquity hampers the lengthening of the subducting slab and hence the associated trench-normal traction.
- In the arcuate part of the subduction zone, the non-lithostatic forces transmitted by the subducting slab to the overriding plate through the subduction interface tend to converge towards the center of the curved trench. Depending on the trench-curvature radius, this induces different tectonic regimes at the NE corner of the CP :
    - When the trench-curvature radius is relatively low, the idealized arc/back-arc regions can undergo a compressive component oriented E-W to ENE-WSW. The compression-to-extension ratio is relatively high (>60%) and the regime may tend towards a transpressive regime.
    - When the trench-curvature radius is relatively high, comparable to the present-day radius of curvature of the LASZ, the compressive component is limited with a compression-to-extension ratio less than 40% and denotes a clear transtensive regime.
- If the overriding plate is sufficiently weak, the trench-curvature radius of a model can increase self-consistently given the related tectonic stress field with a higher predominance of extension in the southernmost portions of the CP. The compressive component in the NE-corner is progressively relieved through time.

- At north, the westward displacement of the transitional plate boundary, which connecting the eastern subduction contact fault to the western transform fault, induces high shear stresses in the forearc area. The transitional plate boundary also acts as an indenter on the overriding plate and can induce a N-to-NE oriented compressive component in the rear back-arc area. This indenter-effect is inversely proportional to the length of the transition plate boundary.

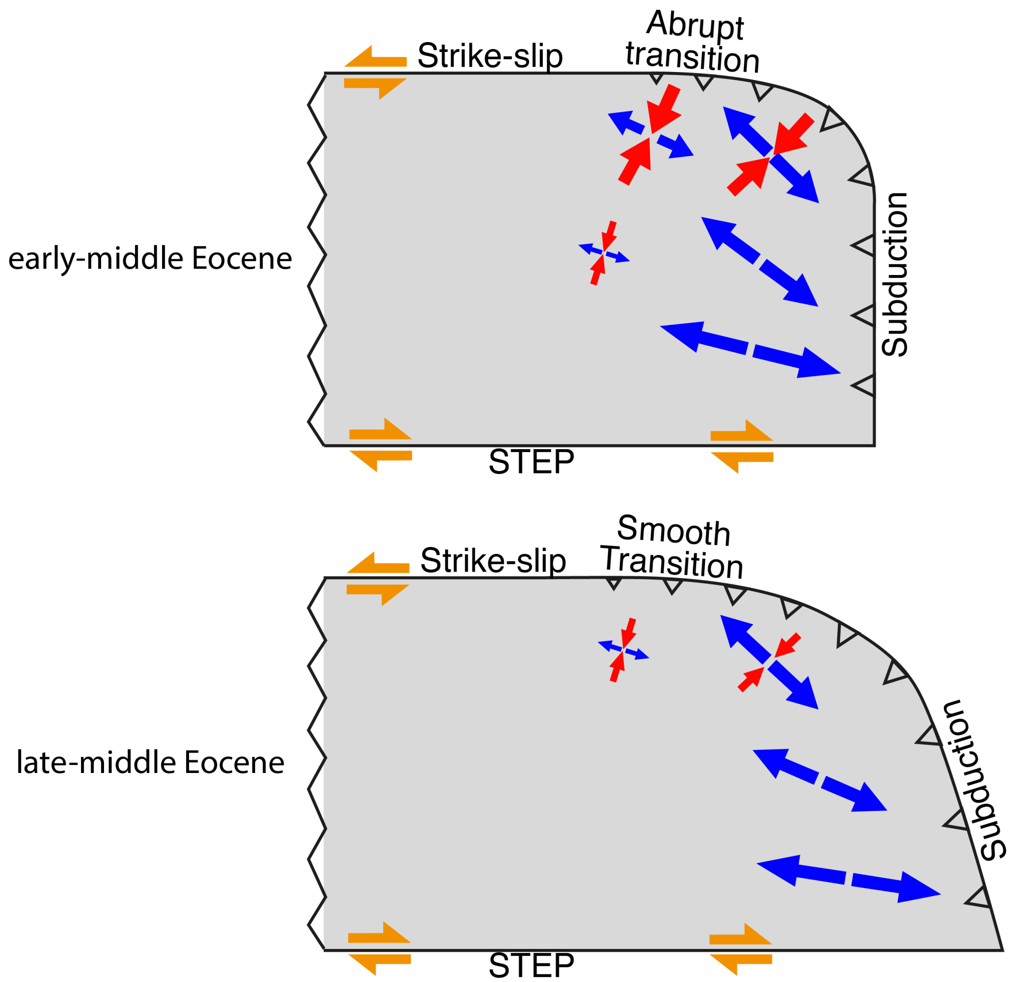

Figure 8: *Sketch of our tectonic model for the spatio-temporal evolution of the tectonic regime in the back-arc of the LASZ during the Eocene*

Based on our modeling results, we suggest that the trench curvature of the LASZ, combined to the northern strike-slip and southern STEP boundaries, was a major contributor to the evolution of the tectonic stresses in the arc and back-arc regions of the eastern Caribbean plate (Fig. 8). Back in the early to middle Eocene (from approximately ~55-50 Ma to ~40-35 Ma), we hypothesize that the trench-radius of curvature in the NE corner of the plate was relatively low (R<<600 km). This facilitated a transpressive regime in the region overlying the obliquely subducting plate in the vicinity of the highly-arcuated trench, and comprised from east to west the Saba Bank, the Virgin Islands and Puerto-Rico. We note however that in our models the compressive component of principal stresses in the NE corner equals, at most, the extensive component. Other factors may thus be required to induce a higher compressive component. As discussed below, the arrival of a buoyant feature such as the Bahamas bank may have enhanced the compressive stresses. In the south, our models suggest that the rollback of the South American oceanic subducting slab may have assisted the opening of the Grenada basin by generating extension pointing towards the southern parts of the subduction trench, as suggested by previous works (Bouysse et al., 1988; Aitken et al., 2011; Garrocq et al., 2021).

Note that just after the jump in the plate boundary between the CP and the NAM, the transitional plate boundary might have been of a reduced length, and might also have helped to reach the conditions of transpression in the rear-back-arc and back-arc areas.

From the middle Eocene onwards, the trench-curvature radius may have increased and caused a relief in the tectonic stresses at the NE corner of the Caribbean plate. This may have facilitated the cessation of transpression in the NE Lesser Antilles by the late Eocene. Part of the increase in the trench-curvature radius may have self-consistenly been induced by the deformation of the Caribbean plate under the North-South varying tectonic regime, as in our model with a weak OP. But we also speculate that the accretion of oceanic crust in the Grenada basin during the middle Eocene assisted the increase in the apparent trench-radius of curvature.

A shift in the tectonic regime of the arc/back-arc of the Lesser Antilles occurred in the late Eocene to early Oligocene period, causing SW-NE extension in the north (Legendre et al., 2018; Cornée et al., 2021) and the end of spreading in the Grenada basin (Garrocq et al., 2021, Fig. 1c). Our models however do not address the cause of such a tectonic reorganization.

5.2 Other implications for the tectonic evolution during the Eocene

Besides addressing a possible (simple) mechanism for explaining the Eocene-tectonic duality in the LASZ, our models may also shed light on other geological regional observations.

Garrocq et al., (2021) have proposed two extensive phases that shaped the Grenada basin from the early to the middle Eocene: a rifting and a spreading stage. The authors proposed a consistent NW-SE direction of extension through both stages. Their spreading direction is compatible with a possible NW-dipping subduction of the Atlantic seafloor in the southernmost part of the LASZ, as suggested by previous tectonic reconstructions (e.g. Pindell and Kennan, 2009). Our models suggest instead that the NW-SE rifting and spreading episodes may also be compatible with a more W-dipping subducting slab. The latter case may therefore be compatible with the approximately N-S oriented outer arc inferred from magnetic anomalies east of the Tobago Basin and which might be Eocene in Age (Allen et al., 2019).

The underthrust of the Venezuela Basin beneath Puerto Rico and Hispaniola at the Muertos Trough accommodated a relative, probably modest (Boschman et al., 2014), convergence between the Caribbean and the North American plates (Fig. 1). The estimated date of formation of the Muertos Trough and the associated thrust deformed belt varies between the Cretaceous (Byrne et al., 1985) and the Miocene (Mann et al., 2002) but several studies have pointed out a possible start at Eocene Times (Mauffret and Leroy 1999; Leroy et al., 2000; Granja-Bruña et al., 2014). It has been generally proposed that the arrival of the buoyant Bahamas platform at the Puerto Rico trench was the trigger of the formation of the thrust belt (Mann et al., 2002; Granja-Bruña et al., 2009; ten Brink et al. 2009). Our models suggest an alternative mechanism in which the rear-back arc region facing the northern transitional plate boundary undergoes a N-to-NE oriented compression. Furthermore, the modeled magnitude of the latter displays an inversely proportional relationship to the length of the transitional plate boundary. Although its length is unknown in the natural case at Eocene times, one may hypothesize that following the jump in the plate boundary (from NE Cuba to N of the Greater Antilles, Fig. 2a) this transition was quite sharp. It follows that intraplate compression might have affected the north of the Venezuela Basin in the early to middle-Eocene and might have been accommodated through its underthrust at the Muertos Trough, releasing the compression at farther distances. At later times, the possible increase in the length of the transitional plate boundary may have limited this compressive component.

According to our models, two tectonic regimes may have coexisted during the Eocene in the arc/back-arc regions of northeastern and northern LASZ. In the former, a transpressive regime may have held in the arcuate NE corner for as long as the trench-curvature radius was relatively low. Slightly west of the NE corner another regional transpressive regime may have resulted from a sharp transitional plate boundary. Based on our modeling, we expect the two areas experiencing the most prominent transpressive regime to slightly migrate westwards through time mostly because of the westward displacement of the transitional plate boundary. As discussed above, following accommodation of inland compression at the Muertos Trough and an increase in the trench-curvature radius, the westward migration of transpression may have been coeval of a strong reduction in the magnitude of the compressive component of the stresses by the late Eocene. We nonetheless acknowledge the existence of evidence for an eastward migration of compressive stresses instead, as recorded by crustal exhumation episodes of decreasing age from Cuba to Puerto Rico (Roman et al., 2020). This eastward migration of compressive events is often regarded as the consequence of the eastward migrating front of the collision with the Bahamas bank which started in Cuba in the Paleocene (Roman et al., 2020). As discussed below, our proposed mechanism may be an additional process to take into account for understanding the geodynamical evolution of the northern Caribbean. Nonetheless, our models also suffer from other few limitations which we discuss below.

5.3 Model limitations

5.3.1 Assumption of an inviscid mantle

In our modeling approach, we only take into account the effect of the ambient mantle through the density contrast (Forsyth and Uyeda, 1975). A viscous mantle may however exert both normal stresses induced and shear stresses on the plates-mantle interface (Tovish et al., 1978; Funiciello et al., 2003b; Lallemand et al., 2008; Royden & Holt, 2020). In particular, the toroidal flow, that is the horizontal-component of mantle flow occurring around the edges of the subducting plate from the rear of the slab towards the front of the slab (Funiciello 2003b; Schellart et al., 2004), induces shear stresses at the base of the plates and may facilitate back-arc opening (Schellart and Moresi 2013; Chen et al., 2016; Alsaif et al., 2020). In the Caribbean, a toroidal flow around the southern termination of the American subducting plate might have triggered the opening of the Grenada basin, while a more oblique subduction at north may have impeded it, thus facilitating a latitudinal duality of surface tectonics. However, present-day mantle flow inferred from regional seismic anisotropy does not resemble to a classical toroidal flow beneath the eastern boundary of the Caribbean plate (Zhu et al., 2020). This may be due to the nearby presence of much larger subduction zones, such as the Andean subduction zone, which may affect the background mantle flow in the LASZ (Russo and Silver, 1994). Back in time, the background mantle flow is unknown and thus strong assumptions would have been needed for carrying an accurate regional modeling. Overall, the modeling approach that we undertake, although neglecting the ambient viscous mantle flow, offers a first-order approximation of the forces transmitted by the subducting slab to the overriding plate and the induced overriding plate surface tectonics.

5.3.2 Structural heterogeneities within the Caribbean Plate

At present-day, the northern Caribbean crust has a relatively homogeneous thickness of ~25-27 km from the back-arc to the forearc (Kopp et al., 2011; Padron et al., 2021). The southern part of the CP is characterized by the presence of a thin (5-10 km) oceanic crust in the Grenada and Tobago basins (Fig. 1) (Christeson et al., 2008; Padron et al., 2021), separated by the post-mid Eocene volcanic arc-crust, that reaches a thickness of 29-33 km beneath the arc islands (Melehkova et al., 2019). West of the Grenada basin, the Aves Ridge has an average thickness of ~25 km comparable with the northern crust (Christeson et al., 2008; Padron et al., 2021). Prior to the rifting episode which triggered the Grenada basin opening, the Caribbean crust was probably more homogeneous along the active arc. The rifting and the oceanic spreading likely induced variations in the strength of the Caribbean plate from North to South. This may have reinforced the duality of the tectonic evolution of the Caribbean plate. In contrast, the homogeneous strength of the overriding plate cannot evolve with time in our models. Moreover, the localization of tectonic stresses nearby the spreading center during the Eocene may have limited the transmission of extensive stresses within the CP. This might have hampered the NNW-oriented extension (due to the southern trench-normal traction) observed in the NE corner of our models, and thus might have promoted a dominant transtensive regime in this area.

5.3 Effect of the subduction-collision of the Bahamas bank

We have not directly addressed the potential effect of the collision of the northern Caribbean plate with the buoyant Bahamas platform (apart our working assumption of a plate boundary jump in the Late Paleocene). Such a collision in Cuba is thought to have played a major role in the tectonic evolution of this region in the Paleocene – early Eocene, inducing ultimately a re-organization of the North America – Caribbean plate boundary. However, the effect of a possible (south)east-ward propagation of the collision front is yet to be determined. For instance, the arrival of the SE-end of the Bahamas platform into the subduction trench facing Puerto-Rico, was suggested to trigger a transpressive regime in the middle to late Eocene (Lao-Davila et al., 2012; 2014; Román et al., 2020). In fact, Wallace et al (2005) & Wallace et al., (2009) proposed a model for the tectonics nearby a transition from collision-to-subduction. In their model, the arrival of a buoyant feature (collision) generates the bending of the margin, and induces prominent compression in the regions facing the collisional segment while potentially inducing back-arc rifting away from the collision. The latter occurs as the bending of the margin is accompanied by a continued slab-rollback which is accommodated by the rotation of micro-forearc blocks. The model has been recently invoked by Philippon et al., (2020b) and Boucard et al., (2021) to explain the formation of V-shaped forearc basins after the late Eocene.

Whether the model could explain the evolution of the LASZ for the entire Eocene remains an open question. The records of compression in Hispaniola indeed points out to a "soft collision" (i.e. leaving few markers of compression, see Section 2), if at all induced by the subduction of the Bahamas platform (van Benthem et al., 2014). Similarly, the record of a rather soft-collisional environment in Puerto-Rico during the Eocene, lead Lao-Davila et al., (2014) to propose that the nature of the buoyant feature entering the subduction trench was a thickened oceanic crust. It is also worth noting that the underthrust of the SE-continuation of the platform offshore Puerto-Rico has also been proposed to take place only later in the Miocene (Mann et al., 2002; Grindlay et al., 2005).

Here, we thus suggest that the effect of the Bahamas collision, if it occurred at Eocene times, may have been, at least, largely assisted by the effect of a nearby subduction under a highly curved trench and perhaps also by the indenter effect induced by a transitional plate boundary. This hypothesis is in line with the work of van Benthem et al., (2014) who proposed that a force exerted by the along-strike displacement of the western-edge of the slab (a "slab edge push") beneath the northern Caribbean plate boundary was the main driver of regional tectonics, and exceeded the effect of the Bahamas platform collision. Although these authors assumed that the Bahamas subduction only started in the Oligocene onwards, a similar force balance may have occurred if the subduction of the platform occurred earlier. Further work should nonetheless be carried out to quantify the joint effect of a (soft-)collision nearby a transitional plate boundary and a time-evolving curved subduction trench.

6. Conclusions

Recent studies have shed light on a singular stress field in the arc/back-arc region of the LASZ for at least part of the Eocene. While the southernmost part underwent extension and oceanic spreading in the Grenada basin, the northern part underwent compression and/or transpression. Our mechanical models of subduction suggest that this Eocene-tectonic duality may have been generated by both a relatively low trench-curvature radius at the NE-corner of the Caribbean plate in the context of asymmetrical Caribbean plate boundaries at the North (from east to west: highly oblique subduction to a strike-slip system) and at the South (a STEP-like behavior). Compression/transpression at north and extension at south may have provoked an increase in the apparent trench-curvature radius, especially because extension was assisted by oceanic spreading at South. Our models suggest that trench bending may have released the compressive component of stresses in the northern part through time.

Acknowledgments

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Appendix A

The governing equations of the subduction mechanical models are as follows. The physical domain $\Omega_t \subset \mathbb{R}^3$ occupied by the solid lithospheric plates at time t are given by the conservation of momentum and the rheological law for a Maxwell viscoelastic body:

$$\begin{cases} \operatorname{div} \boldsymbol{\sigma} + \rho\, \boldsymbol{g} = \mathbf{0} & \text{in } \Omega_t, \\ \dfrac{D\boldsymbol{\sigma}}{Dt} = 2\mu\dot{\boldsymbol{\epsilon}} + \lambda \operatorname{tr}(\dot{\boldsymbol{\epsilon}})\boldsymbol{I} + \dfrac{\mu}{\eta_l} \operatorname{dev} \boldsymbol{\sigma} & \text{in } \Omega_t, \end{cases} \tag{1}$$

where σ is the Cauchy stress field, ρ is the lithosphere density, $\boldsymbol{g}$ is the vector of gravity acceleration, and $\dot{\boldsymbol{\epsilon}} = \frac{1}{2}(\nabla \boldsymbol{v} + \nabla^T \boldsymbol{v})$ is the Eulerian strain-rate tensor given by the symmetric gradient of the velocity field $\boldsymbol{v}$. The operator $^{D\,\cdot}/_{Dt}$ represents an objective time derivative. $\boldsymbol{I}$ is the identity tensor. tr and dev are the trace and deviatoric operators. η_l is the viscosity of the plates, and λ and μ are the Lamé parameters:

$$\lambda = \frac{E\nu}{(1+\nu)(1-2\nu)}, \mu = \frac{E}{2(1+\nu)} \tag{2}$$

with E and ν the Young's modulus and the Poisson's ratio, respectively.

The plate-plate mechanical contact on the interface Γ_c is modeled with the Sigorini relation (no interpenetration, no attraction and complementary condition) and the Coulomb friction law:

$$\begin{cases} \delta v_n \le 0\,, \quad \sigma_n \le 0\,, \quad \delta v \sigma_n = 0 \text{ on } \Gamma_c, \\ |\sigma_t| \le -\mu\sigma_n \text{ if } \delta v_t = 0 \text{ on } \Gamma_c, \\ \sigma_t = \mu\sigma_t \dfrac{\delta v_t}{|\delta v_t|} \text{ if } \delta v_t \ne 0 \text{ on } \Gamma_c, \end{cases} \tag{3}$$

where δv_n and δv_t are the outward normal and tangential components, respectively, of the relative velocity between two points in contact, and μ is the effective Coulomb friction coefficient. σ_n and σ_t are the normal and tangential stresses at the point of contact.

The lithospheric plate interfaces in contact with the inviscid mantle are subjected to the lithostatic pressure:

$$p_{litho} = \frac{1}{\beta} \ln(1 - \beta \rho_m^0 g z) \tag{4}$$

where β is the compressibility modulus of the mantle, assumed to be constant, ρ_m^0 is the density at the base of the lithospheric plates, z is the depth and $g = |\boldsymbol{g}|$ is the gravity acceleration. See Hassani et al., (1997) for further details.

We use the finite element code ADELI (Hassani et al., 1997) to compute an approximate solution of the equations (1)-(3).

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