

# Ocean-continent subduction cannot be initiated without preceding intra-oceanic subduction!

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# Ocean-continent subduction cannot be initiated without preceding intra-oceanic subduction!

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The formation of new subduction zones is a key element of plate tectonics and the Wilson cycle, and many different controlling mechanisms have been proposed to initiate subduction. Here, we provide a brief overview of the known scenarios of subduction initiation in intra-oceanic and ocean-continent tectonic settings. Intra-oceanic subduction is most commonly associated with mechanical heterogeneities within the oceanic lithosphere, such as pre-existing fracture zones, spreading ridges, and transform faults. Numerous and well-recognized examples of new active subduction zones formed in intra-oceanic environments during the Cenozoic, suggesting that the initiation of ocean-ocean subduction must be a routine process that occurs “easily and frequently” in the mode of plate tectonics currently operating on Earth. On the contrary, the most traditional mechanisms for the establishment of classic self-sustaining ocean-continent subduction—passive margin collapse and subduction transference—are surprisingly rare in observations and difficult to reproduce in numerical models. Two alternative scenarios—polarity reversal and lateral propagation-induced subduction initiation—are in contrast much better documented in nature and experimentally. However, switching of subduction polarity due to arc-continent collision and lateral transmission of subducting plate boundaries are both inextricably linked to pre-existing intra-oceanic convergence. We, therefore, conclude that the onset of classic ocean-continent subduction zones is possible only through the transition from a former intra-oceanic subduction system. This transition is likely facilitated by the ductile damage accumulation and stress concentration across the aging continental margin. From this perspective, the future closure of the Atlantic Ocean can be viewed as an archetypal example of the role of transitional process between intra-oceanic subduction (Lesser Antilles) and the development of a new subduction zone at a passive continental margin (eastern North America).

## KEYWORDS

subduction initiation, transform fault collapse, passive margin collapse, subduction transference, polarity reversal, lateral propagation, Caribbean plateau, Atlantic Ocean

## Introduction

Subduction is a key element of terrestrial plate tectonics (Stern, 2002). Although the periodic events of opening and closure of oceanic basins (Wilson, 1966) suggest that subduction must initiate frequently in geologic history, the underlying mechanisms that trigger subduction are not fully understood (Stern, 2004; Cloetingh et al., 2021; Yang, 2022). Difficulties in identifying and characterizing subduction initiation in nature are related to poor accessibility of data, lack of *a priori* knowledge about where subduction begins, incomplete understanding of the geologic, petrologic, and geochemical signatures, as well as the physical parameters required for the emergence of new subduction zones (Gerya, 2011; Stern and Gerya, 2018; Gerya, 2022). A further complication is that the conditions and dynamics of subduction initiation at mature continental margins (Nikolaeva et al., 2010, 2011; Marques et al., 2013, 2014) differ significantly from those in intra-oceanic environments (Nikolaeva et al., 2008; Zhu et al., 2009; Dymkova and Gerya, 2013).

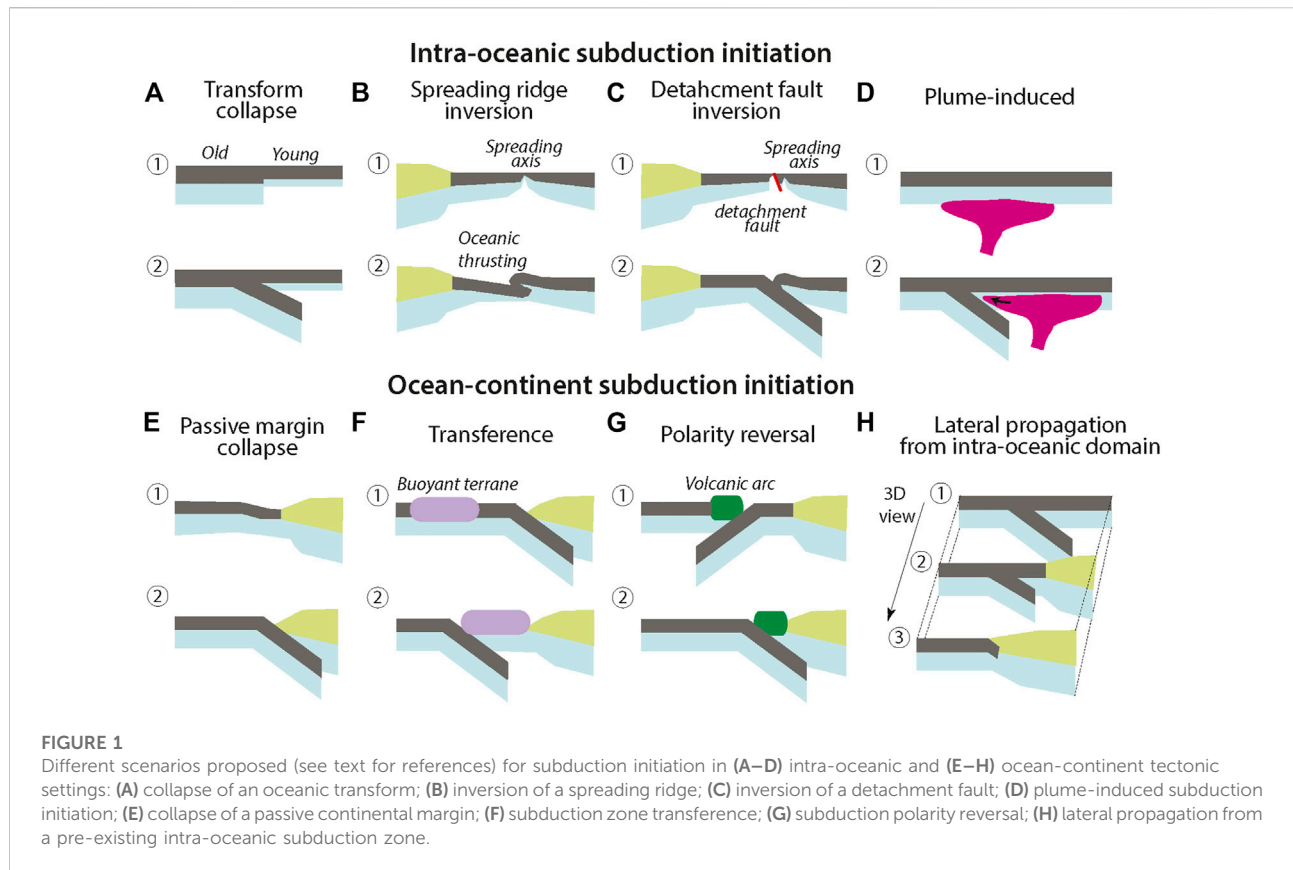
Traditionally, subduction initiation scenarios are divided into two main types (Stern, 2004): 1) “spontaneous”, caused by internal gravitational instability (i.e., local, vertically-oriented forces originating *in situ*); and 2) “induced”, triggered by ongoing plate convergence (i.e., horizontally-oriented far-field tectonic forces). However, recent studies show that it can be challenging to distinguish between these end-members (Zhang and Leng, 2021; Zhou and Wada, 2021). For example, oceanic transform faults that have been considered as potential sites for purely spontaneous, gravity-driven collapse (Karig, 1982; Matsumoto and Tomoda, 1983; Dymkova and Gerya, 2013; Maunder et al., 2020) can hardly evolve into a subduction zone without either a horizontal or vertical external forcing (Leng et al., 2012; Arcay et al., 2020). Collapse of passive continental margins, another traditional example of the spontaneous mechanism (Vlaar and Wortel, 1976; Cloetingh et al., 1982; Nikolaeva et al., 2010), may also require significant additional forces (Auzemery et al., 2021; Candiotti et al., 2022) originating from topographic gradients (Marques et al., 2013) and/or mantle suction induced by adjacent subduction-related flow (Baes and Sobolev, 2017). In this regard, recent systematic reviews of well-documented subduction initiations in the Late Mesozoic and Cenozoic fundamentally question the feasibility of spontaneous mechanisms, suggesting that horizontally forced scenarios predominate (Cramer et al., 2020; Lallemand and Arcay, 2021). However, it is noteworthy that the observed temporal transitions in the stress regime during the onset of subduction may indicate a multistage evolution in which early horizontal forces dominate before subduction becomes self-sustaining, and vertical forces take over with time as the sinking slab begins to pull the subducting plate independently (Shuck et al., 2022). This

suggests that the current system for classifying subduction zones based on whether horizontal or vertical forces are responsible for their formation is oversimplified (Cramer, 2022).

A particularly relevant aspect of the debate over “induced” vs “spontaneous” modes of subduction initiation regards the type of overriding plate (oceanic or continental), upon which we focus our review of the mechanisms controlling the formation of new subduction zones. We first consider models of subduction initiation typical of intra-oceanic environments, and then provide an overview of scenarios which are more appropriate for the onset of classic ocean-continent subduction. We argue that the most viable mechanisms for establishing self-sustaining subduction of the oceanic plate beneath the continent are intrinsically connected with the preceding intra-oceanic subduction, the triggering of which, in turn, is a very common process that occurred frequently during the Cenozoic (Gurnis et al., 2004; Cramer et al., 2020; Lallemand and Arcay, 2021). Following this line of reasoning, future closure of the Atlantic Ocean is unlikely to occur by gravitational collapse of mature continental margins, but rather by cascading subduction initiations in the Caribbean region, where ongoing subduction of Atlantic lithosphere beneath the Lesser Antilles is prone to lateral transfer toward the western Atlantic passive margin along eastern North America (Zhou et al., 2020).

## Intra-oceanic subduction initiation: “Easy and frequently”

The onset of subduction within the oceanic lithosphere has traditionally been associated with abrupt lateral heterogeneities in its structure (Figures 1A–C). Collapse of oceanic transform faults is the most typical mechanism for triggering intra-oceanic subduction (Uyeda and Ben-Avraham, 1972; Karig, 1982; Whattam and Stern, 2011). In this case, subduction nucleates along the active transform boundary, separating younger (less-dense) lithosphere from older (more-dense) lithosphere (Stern and Bloomer, 1992). Such lateral buoyancy contrasts may also be enhanced by pre-existing or fluid-induced rheological weakening of the plate interface (Dymkova and Gerya, 2013; Faccenna et al., 2018) and/or by accompanying external tectonic forces (Arcay et al., 2020). This mechanism has been extensively explored in numerous numerical (Hall et al., 2003; Gerya et al., 2008; Nikolaeva et al., 2008; Zhu et al., 2009; Zhou et al., 2018) and analog (Boutelier and Beckett, 2018) modelling studies. A new subduction zone can also form by inversion of an oceanic spreading ridge (Duretz et al., 2016; Beaussier et al., 2019) possibly assisted by inherited oceanic detachment faults (Toth and Gurnis, 1998; Maffione et al., 2015; Gülcher et al., 2019). When these structures are close to the passive margin, the process of subduction initiation is quickly followed by the process of obduction, during which regional-scale fragments of oceanic



lithosphere (ophiolites) are emplaced over the adjacent continental lithosphere (Van Hinsbergen, et al., 2015; Agard et al., 2016). An alternative mechanism that does not rely on pre-defined heterogeneities and weaknesses in the lithosphere is plume-induced subduction initiation (Figure 1D; see also review by Baes et al. (2021) and references therein). In this scenario, a sufficiently large and hot plume head ruptures the overlying plate, leading to self-sustaining sinking of the adjacent portion of the lithosphere (Ueda et al., 2008; Gerya et al., 2015; Baes et al., 2016, 2020).

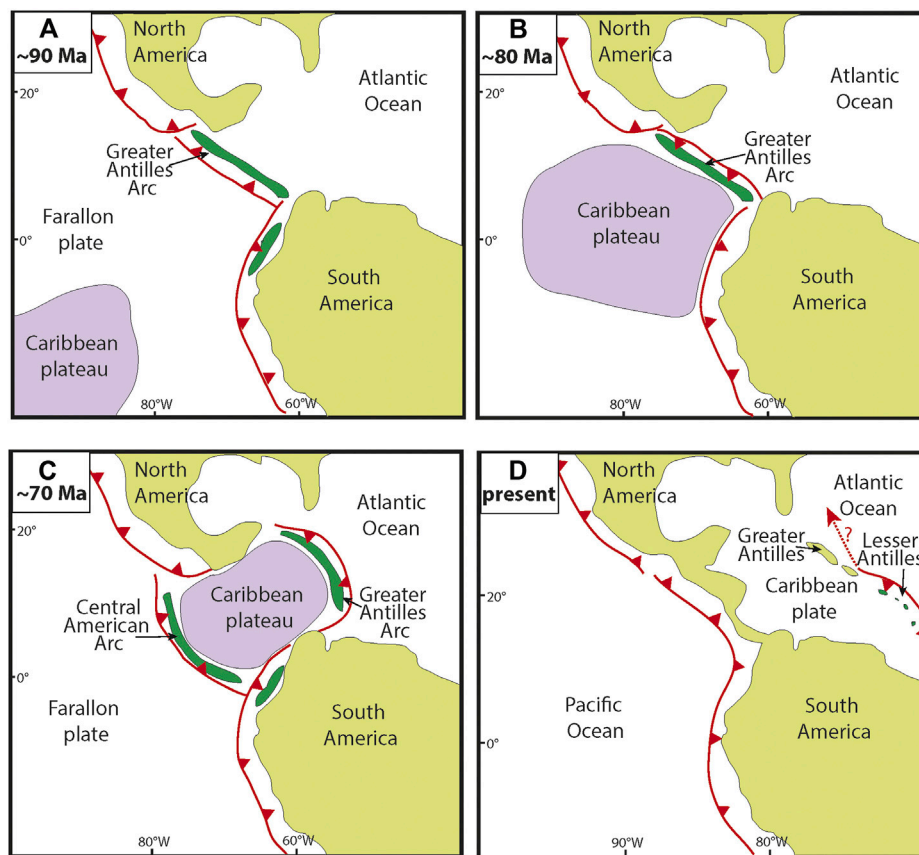
All the above mechanisms for intra-oceanic subduction initiation are viable in terms of both observational records and reproducibility in experiments. This is also consistent with the notion that most Tertiary and earlier subduction zones are intra-oceanic, with relatively simple scenarios for their triggering (Gurnis et al., 2004; Cramer et al., 2020; Lallemand and Arcay, 2021).

## Passive margin collapse and subduction transference: Traditional, but rarely working

Since the inception of the plate-tectonic theory (Wilson, 1966; Dewey et al., 1973), it has been assumed that the

primary mechanism of subduction initiation is collapse of the passive continental margin (Figure 1E) due to increasing negative buoyancy of the aging lithosphere in an opening ocean (Vlaar and Wortel, 1976; Davies, 1999). However, simultaneously with this gravitational instability, the strength of the oceanic plate is rapidly increasing, posing a serious obstacle to continental margin collapse (Cloetingh et al., 1982, 1989), even in the presence of sedimentary loading (Cloetingh et al., 1982, 1984) and/or additional forcing due to topographic gradients (Marques et al., 2013). Recently, the ever-growing strength of an aging passive continental margin has been challenged by theoretical arguments showing that the accumulation of ductile damage in the margin can critically lower its strength with time (Bercovici and Mulukova, 2021).

Although tectonic inversion of passive continental margins has been widely reported (Lundin and Doré, 2002; Lundin et al., 2013), none of these Atlantic-type margins has yet evolved into a subduction zone. Nevertheless, numerical modelling studies have continued to search for potential sites for future subduction at present-day passive margins, such as the mechanically weak southern Brazilian margin (Nikolaeva et al., 2011; Marques et al., 2013), the Argentine Basin and the U.S. East Coast, which are likely subject to plate suction from adjacent active, eastward-dipping subduction zones (Baes and Sobolev, 2017), as well as the East



**FIGURE 2**

From subduction of the Farallon plate to closure of the Atlantic Ocean by a cascade of subduction initiations. (A–C) Geodynamic model for the evolution of the Caribbean region in Late Cretaceous: (A) north-eastward subduction of the Farallon plate; (B) collision of the Caribbean plateau accompanied by subduction polarity reversal; (C) subduction transference with formation of the Central American Arc behind the Caribbean plateau (from Yang, 2022). (D) Predicted development of a future ocean-continent subduction zone (eastern North America) by lateral propagation of the currently on-going Lesser Antilles subduction (Zhou et al., 2020).

African margin (Gerya, 2011) thermally weakened by the African superplume (Mulibo and Nyblade, 2013; Koptev et al., 2015, 2018). However, despite numerical (Nikolaeva et al., 2010; Candiotti et al., 2022) and laboratory (Faccenna et al., 1999; Auzemery et al., 2021) model inferences, no irrefutable natural example of initiated self-sustained subduction at a passive margin has yet been documented.

Subduction zone transference is a composite dynamic process that invokes both the termination of subduction by terrane collision/accretion and the onset of subduction on the backside of the colliding block (Figure 1F). When a buoyant block of lithosphere corresponding to an oceanic plateau or (micro)-continent collides with the trench, subduction comes to a local halt. However, convergence continues due to the new subduction zone with the same dip direction at the adjacent passive margin (Stern, 2004). As for the proposed scenario of passive margin collapse, subduction zone transference seems to carry a paradox in view of the temporal geotectonic evolution of the Earth. On the one hand, multiple ribbon-like (micro)-

continents were repeatedly drifting away from Gondwana and subsequently accreted to the Eurasian continent with the re-establishment of an active subduction zone at their backside during the evolution of Tethyan systems since the Paleozoic (Yang, 2022). On the other hand, not a single ocean-continent subduction zone was triggered by subduction zone transference in Cenozoic time. The archetypal example of such a “failed” subduction zone transference is the collision between India and Eurasia, on-going since ~50 Ma, which did not give rise to a new subduction zone along the southern Indian margin (Van Hinsbergen et al., 2019). Thus, subduction zone transference inferred from Paleozoic plate-tectonic reconstructions is surprisingly frequent (e.g., Torsvik, 2019; Wan et al., 2019), considering the lack of confirmed cases for this mechanism in the Cenozoic, which includes the best preserved geodynamic record (Yang, 2022). This process is also difficult to reproduce in numerical models, which generally show oceanward trench jumping over continued subduction (Tetreault and Buitert,

2012; Vogt and Gerya, 2014), rather than generating true subduction zone transference. Only for extreme conditions adopted in the experiments, requiring continued forced convergence instead of free subduction combined with a pre-defined weakness of the backward passive margin of the collided block, subduction can be initiated by subduction zone transference (Zhong and Li, 2020). In the case of the continental collision between India and Eurasia, it was the lack of sufficient weakness that prevented subduction initiation at the passive margin of India (Zhong and Li, 2022).

It appears, therefore, that the two most popular scenarios for triggering ocean-continent subduction face first-order challenges in terms of consistency with plate-tectonic reconstructions and reproducibility in numerical simulations.

## Polarity reversal and lateral propagation: Viable alternatives

Subduction polarity reversal is triggered by the arrival of buoyant lithosphere of an adjacent continent (or a thick oceanic plateau) into the trench. As a result, the subducting and overriding plates exchange roles (Stern, 2004) and the initially overlying lithosphere starts to subduct (Figure 1G). Subduction polarity reversal has been demonstrated to be a viable mechanism to explain the possible formation of new subduction zones during the Cenozoic and earlier (see review by Yang (2022) and references therein). The Taiwan and Kamchatka orogens are classic and well-documented examples of the role of this process in the formation of new zones of ocean-continent subduction. The Taiwan orogen formed as a consequence of the oblique Miocene arc-continent collision between the Eurasian plate and the Philippine Sea plate, where the break-off of the originally southward-dipping Eurasian oceanic plate was followed by a change in subduction polarity that resulted in northward-dipping subduction of the Philippine Sea plate beneath the Eurasian continent (Teng et al., 2000; Clift et al., 2003; Ustaszewski et al., 2012). In the Kamchatka region, during the Paleocene, the oceanic part of the Eurasian plate subducted south-eastward under the Pacific Ocean. Subsequently, during the Eocene, the volcanic arc collided with the Eurasian continental margin, causing initiation of north-westward subduction of the oceanic Pacific lithosphere (Hourigan et al., 2009; Konstantinovskaya et al., 2011). It is important to note that the onset of subduction by polarity reversal may not be as common as the initiation of intra-oceanic subduction because of the different timescales of these processes: the time interval required to trigger intra-oceanic subduction by fault collapse or inversion is on the order of only 5 Myr (Nikolaeva et al., 2008; Duretz et al., 2016; Lallemand and Arcay, 2021), whereas it can take up to several tens of Myr for oceanic lithosphere to be consumed before proceeding to subduction beneath a continent (or oceanic plateau) through a change in subduction polarity.

Recently, several successful 2D (Cramer and Tackley, 2015; Sun et al., 2021; Almeida et al., 2022b) and 3D (Almeida et al., 2022a) numerical models have been developed that are capable of mimicking the key elements of subduction polarity reversal in intra-oceanic environments, inspired by the archetypal example of the Miocene collision of the Ontong Java Plateau with the Solomon Arc in the south-western Pacific Ocean (Cooper and Taylor, 1985; Petterson et al., 1999). In addition, a completely spontaneous reversal of subduction polarity in response to an arc-continent collision has been reproduced in a pioneering modelling study by Zhang and Leng (2021).

Another important advance in subduction initiation modelling was made by Zhou et al. (2020), who showed that a pre-existing intra-oceanic subduction zone can propagate laterally toward adjacent weak continental margins (Figure 1H). According to this study, a new subduction zone is expected to develop along the Northern American Atlantic coast, north of the Lesser Antilles. Possible passive margin weakening with its aging (Bercovici and Mulukova, 2021) may play critical role for enabling this scenario. Subduction propagation has also been inferred from tectonic reconstructions in various regions of the world, including the Indonesian subduction zone in the Banda arc region (Hall, 2012) and the subduction of the Nazca plate along the Andes (Chen et al., 2019). Subduction initiation along the western European margin may also arise from future westward migration of the Gibraltar slab into the east-central Atlantic (Duarte et al., 2013).

In view of the above, and differently from passive margin collapse and subduction transference, subduction polarity reversal and lateral propagation can be considered as viable modes of subduction initiation in ocean-continent tectonic settings.

## Archetypal examples from the past and toward the future: how Farallon plate subduction closes the Atlantic Ocean

The Caribbean region provides a well-documented natural laboratory to serve as a test-bed for exploring the different scenarios of subduction initiation reviewed above (Figure 2). In Cretaceous time, north-eastward subduction of the Farallon plate (Figure 2A) was followed by collision of the Caribbean plateau—the thickened part of the oceanic lithosphere (Kerr et al., 2003) formed by magmatism associated with the Galapagos hotspot ~90 Ma (Thompson et al., 2004)—with the Greater Antilles Arc and north-western South America at ~80 Ma (Neil et al., 2011; Buchs et al., 2018). In the Greater Antilles, this collision caused subduction polarity reversal, resulting in the formation of a new subduction dipping in south-western direction below the Caribbean plateau (Figure 2B). A subsequent subduction transference (Figure 2C) formed the Central American Arc behind the oceanic plateau (Yang, 2022). The south-westward-dipping

subduction of the Atlantic oceanic lithosphere is marked by a pronounced trench retreat (Munch et al., 2020), which allowed the insertion of the Caribbean plateau between the North and South American continents (Hoernle et al., 2002). As mentioned above, this narrow segment of intra-oceanic subduction in the central Atlantic may in the future extend northward (Figure 2D) toward the present passive margin of North America (Zhou et al., 2020). Such cascading subduction onsets, which took and might take place in different modes, shows how subduction on one side of the continent can effectively transform the passive margin along the opposite side of the same continent into an active margin. Global changes in the balance of plate-tectonic forces and plate motions triggered by passive to active margin transitions may eventually lead to the closure of entire oceanic basins such as the present-day Atlantic.

As pointed out in our review, the initiation of a classic ocean-continent subduction zone is intrinsically linked to the precursor intra-oceanic subduction. At the same time, the triggering of intra-oceanic subduction seems to be a routine geodynamic process on Earth. We, therefore, conclude that intra-oceanic subduction plays a crucial role not only in plate-tectonic reorganizations in the oceans, but also in the initiation of ocean-continent subduction, key in the closure of oceanic basins and the entire Wilson cycle.

## Author contributions

AK developed the conceptual idea and took the lead in writing the manuscript. Preparation of the manuscript was done by AK and SC with contributions from all co-authors.

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