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Breaking the Caribbean Plate: Subduction Initiation Beneath the Northern Margin of Panama

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Key Points:

- We present a newly relocated earthquake catalog for Northwestern South America and eastern Panama
- This catalog includes the 25 May 2025 Mw 6.5 earthquake and aftershocks that show subduction of the Caribbean Plate beneath eastern Panama
- The initiation of the subduction of the Caribbean Plate beneath Panama occurred as early as 39 Ma and likely no later than 20 Ma

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract The initiation of subduction zones is a poorly understood but core plate tectonic process. One unknown is how and under what conditions previously contiguous plates break. Here we present a comprehensive assessment of the Northern Panama Subduction Zone (NPSZ) where the Caribbean Plate is subducting to the SSW beneath Panama. Because the Panama arc was built onto the Caribbean Plate, the existence of the NPSZ means that the Caribbean Plate must have broken. The significant crustal thickness (~20 km) and age (>90 Ma) of the Caribbean Plate make the NPSZ the closest analog to passive margin failure known. We use evidence from the 25 May 2025 Mw 6.5 megathrust earthquake northeast of Panama included in a newly refined earthquake catalog to identify the geometry of the downgoing plate. We combine these with plate reconstructions to study the initiation of the NPSZ, its subsequent evolution, and its tectonic implications.

Plain Language Summary The subduction of oceanic plates underneath a continental or oceanic plate is a key ingredient of tectonic plate theory. However, how the subduction process started is still a topic of debate, and present-day examples of subduction initiation are not easily found and not entirely understood. We present strong seismological evidence of subduction of the Caribbean Plate underneath the Panama Arc along the Northern Panama Subduction Zone. Since the Panama Arc was once a part of the Caribbean Plate, this evidence means that the Caribbean Plate must have been broken. Using existing plate reconstruction models, we study the initiation of the NPSZ, its evolution and tectonic implications.

1. Introduction

Since the advent of plate tectonic theory, the processes underlying the development of new subduction zones have proved challenging to describe fully (McKenzie, 1977; Vlaar & Wortel, 1976). The importance of these processes cannot be understated, as they lie central to our understanding of why Earth remains the only planet known with active plate tectonics (Stern and Gerya, 2018). What has become clear is that there is no one explanation or preferred setting for all instances of subduction zone initiation (SZI). Indeed, there is not even a universally agreed upon framework with which to describe SZI events.

What follows is the most comprehensive-to-date assessment of a young, often overlooked SZI event that lies along the northeastern coast of Panama. Here, we refer to this young convergent plate boundary as the Northern Panama Subduction Zone (NPSZ). We present the state-of-the-art evidence for the existence of this subduction zone, its characteristics, and the age of subduction initiation. We place this subduction zone in the context of the tectonic setting that led to its initiation and discuss its implications for understanding the tectonic evolution of Northwestern South America (NWSA). Additionally, we examine its relevance for assessing seismic hazards along the southwestern Caribbean coast. Based on our tectonic evolution, we discuss the NPSZ SZI in terms of existing SZI archetypes and stages of evolution.

1.1. Tectonic History of the Isthmus of Panama

For this work, we distinguish between the modern-day contiguous landmass of the "Isthmus of Panama" that connects Central America to South America (Figure 1), from the earlier, at times non-contiguous intra-oceanic "Panama arc." Geologically, the Panama arc comprises four blocks that are, from east to west, the Choco Block (Block A—Figure 1c) which has been accreted onto the western margin of Colombia and is limited to the

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east by the Uramita Suture (Duque-Caro, 1990), the San Blas Block (Block B), the Canal Block (Block C) and the Azuero Block (Block D). The latter three are part of the present-day Isthmus.

The Panama arc was built beginning in the Upper Cretaceous (Wegner et al., 2011) as a largely submerged intraoceanic volcanic arc. This arc developed due to the subduction of the Farallon Plate beneath the thick, young, and buoyant Caribbean oceanic plateau (also known as Caribbean Large Igneous Province, CLIP [Pindell & Kennan, 2009]). This plateau (~95–83 Ma [Dürkefälden et al., 2019; Sinton et al., 1998]) constitutes the basement of the Isthmus and is exposed around the region (Ariza-Acero et al., 2022; Buchs et al., 2010; Kerr et al., 1997; Kolarsky et al., 1995; Lissinna, 2005; Montes, McFadden, et al., 2012; Ortiz-Guerrero et al., 2024) Subduction of the Farallon plate beneath the Caribbean plateau is evidenced by a belt of Campanian to Eocene (83–40 Ma, see Figure 1c) magmatic bodies that overlie the Caribbean basement and form the roots of the Panama arc (Corral et al., 2011; Hoernle et al., 2008; Lissinna, 2005; Montes, Bayona, et al., 2012, 2015).

Following this period of intraoceanic arc activity, parts of the Panama arc underwent a period of intense deformation and fracturing. Volcanic activity ended at ~39 Ma east of the canal fault zone (CFZ) (i.e. blocks A and B) (Farris et al., 2011; Montes, McFadden, et al., 2012; Ortiz-Guerrero et al., 2024). This magmatic lull is coeval with the initiation of sub-aerial deposition of coarse-grained Eocene clastics and faster cooling rates in the roots of the arc in the same blocks (Farris et al., 2011; Ramirez et al., 2016). Deformation at this time may have been related to the main phase of oroclinal bending that ultimately formed the modern Isthmus of Panama (Montes, McFadden, et al., 2012; Rodriguez Parra et al., 2017). Much of this deformation is focused along a large strike-slip structure (see CFZ fault in Figure 1), that displaced the magmatic arc by nearly 100 km left-laterally (Montes, McFadden, et al., 2012; Wolters, 1986).

Around 21 Ma, a slab window opened (McGirr et al., 2021) due to the breakup of the Farallon plate and the ensuing development of a strike-slip plate boundary between the Panama arc and the new, eastward moving Nazca plate. By Middle Miocene times, the Panama arc was colliding with South America as evidenced by the exchange of fluvial detritus between the southeastern tip of the Panama arc (blocks A and B in Figure 1) and the northwestern Andes (León et al., 2018; Montes et al., 2015; Vallejo-Hincapié et al., 2024), and the changes in depositional environments in the syn- and postcollisional sedimentary sequences of the Darien Basin in eastern Panama (Coates et al., 2004). Active volcanism today continues to be limited to areas west of the CFZ.

1.2. Previous Work on the Modern NPSZ

We are not the first to identify south-dipping subduction beneath Panama. Indeed, previous authors have described subduction zone, or at least overthrusting, along the northern margin of the Isthmus of Panama for almost 50 years (Adamek et al., 1988; Camacho et al., 2010; Jordan, 1975; Wolters, 1986). The most detailed previous description of subduction along the NPSZ comes from Camacho et al. (2010) who describe ongoing subduction of the Caribbean Plate just west of the apex of the Isthmus. The downgoing slab is identified based on sparse seismicity that clearly delineates a south-dipping Wadati-Benioff zone extending to at least 80 km depth. The full catalog of hypocenters plotted by Camacho et al. (2010) is not provided in their work, but we plot those hypocentral locations they do identify (provided in a list of event focal mechanisms). The trench for the downgoing plate described by Camacho et al. (2010) lies along the northern margin of the Northern Panama Deformed Belt (NPDB), a region of deformation whose provenance and age is unknown, and that extends up to 130 km away from the northern coast of Panama. The work of Camacho et al. (2010) complements earlier work (Camacho & Víquez, 1993; Mendoza & Nishenko, 1989) describing damaging historic seismicity in this area, including the 7 September 1882 Ms = 7.9 event that caused widespread damage across Panama from near the Costa Rican border to northwestern Colombia. A recent hazards assessment for Panama identifies the NPSZ as a region capable of generating a megathrust event of Mw = 7.5 (Alvarado et al., 2017). Despite its importance as a significant source of hazard, few constraints have been available on the initiation and tectonic evolution of the NPSZ.

2. New Evidence for Subduction of the Caribbean Plate Beneath Panama

On 25 May 2023, a Mw6.5 earthquake struck the south easternmost Caribbean coast of Panama at ~10 km depth. This was an oblique thrust event with a strike, dip, and rake of 153°, 17°, and 142° respectively (Ekström et al., 2012). Focal mechanisms were derived at the Servicio Geologico Colombiano (SGC) (Dionicio et al., 2023) using four different approaches. These show broad consistency with the GCMT results (ISOLA (Sokos &

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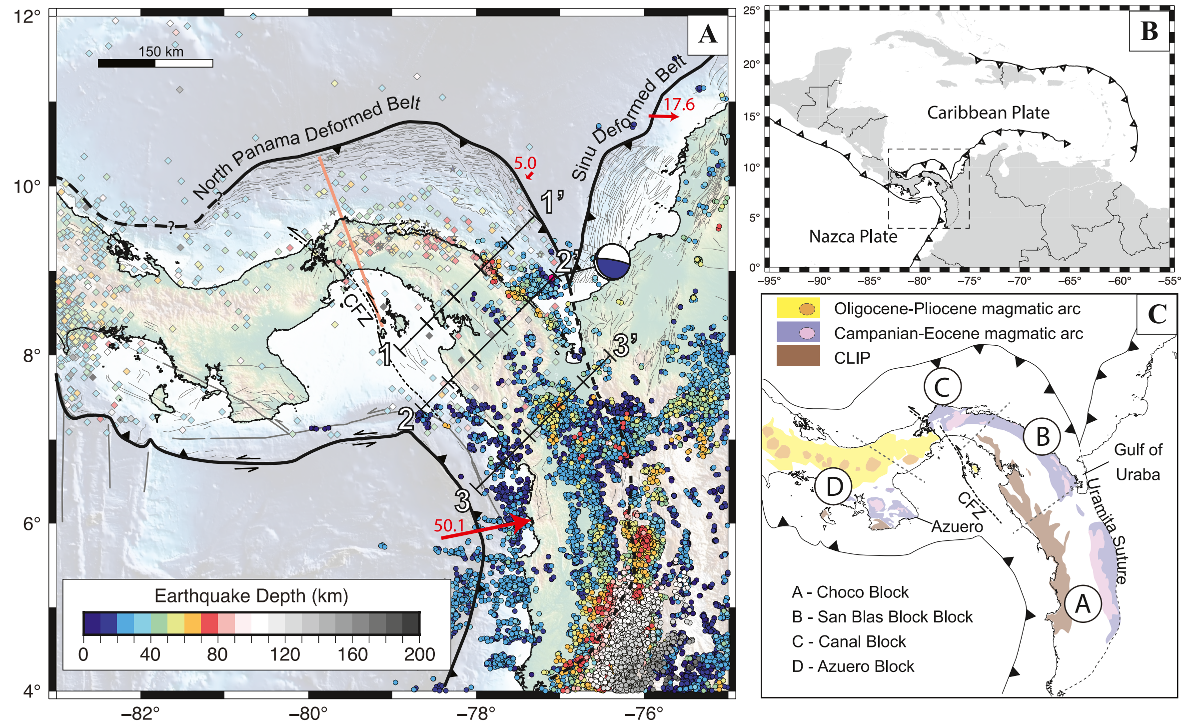

Figure 1. Present day Panama Arc. Panel A shows the catalog and relocated seismicity in the Panama Isthmus and NW South America. The 25 May 2023 Mw 6.5 earthquake focal mechanism is shown as well. Diamonds show events from the Reviewed ISC Catalog (1990–2022) (ISC, 2025; Storchak et al., 2020). Stars are from events with hypocentral locations identified in Camacho et al. (2010). Circles show events from the present work. All are color coded according to depth. Red arrows indicate relative plate motions from Jarrin et al. (2023) in mm/yr. Numbers adjacent to arrows indicate relative plate velocity in mm/yr. The orange line shows the location of the Camacho et al. (2010) profile. Profiles 1-1′, 2-2′, and 3-3′ are shown in Figure 2. Tick marks along profile are at 50 km intervals. Panel B shows the broader plate tectonic context of our study area. Dashed box indicates area covered in Panel A. Panel C shows the present-day position of magmatic arcs from the Panama arc, the Canal Fault Zone (CFZ). The arc is divided in four microplates or blocks based on the work by Montes, McFadden, et al. (2012) and Rodriguez Parra et al. (2017).

Zahradnik, 2008, 2013): 151°, 18°, and 138° (Figure S1 in Supporting Information S1); Wphase (Kanamori & Rivera, 2008): 157°, 16°, and 140°; SCMTV (Hanka et al., 2010; Minson & Dreger, 2008): 149°, 47°, and 136°; SWIFT (Nakano et al., 2008): 120°, 23°, and 85°). Focal mechanisms for other regional events from the GCMT catalog since 2011 show a consistent pattern of a dominating oblique thrust mechanisms (Figure S2 in Supporting Information S1). The US Geological Survey finite fault plane solution indicates that the shallow SW-dipping fault plane extended ∼20 × 25 km, with a maximum slip of ∼0.6 m (Hayes, 2017), consistent with a SSW dipping megathrust earthquake. The magnitude and mechanism of this event refocused attention on this region and its potential for megathrust seismicity (see Figure S2 in Supporting Information S1). We examine the region of the 25 May 2025 Mw 6.5 event by combining existing catalogs of earthquake locations and focal mechanisms (Adamek et al., 1988; Camacho et al., 2010; Ekström et al., 2012) with a newly relocated catalog of seismicity recorded by the Colombian National Seismic Network (Dionicio et al., 2025 in preparation). The relocated catalog (Figure S3 in Supporting Information S1) is obtained using a double-difference algorithm (Waldhauser & Ellsworth, 2000) using both the original catalog manual picks and relative arrival times based on cross-correlations. We used a similar methodology to Yano et al. (2017), where, based on inter-event distances, we calculate relative arrival times using cross-correlations. The catalog is partitioned into 1° × 1° boxes, and re-locations are performed on each box. The final catalog is obtained from the average locations of the events in each individual box. A more complete description of the relocation steps taken can be found in the Supporting Information S1.

The relocated catalog in the area of interest originally contains more than 1,500 events starting from 2018, including the aftershock sequence of the 25 May 2025 Mw 6.5 earthquake (Figure 1, Figure S4 in Supporting Information S1 for aftershocks). The initial catalog is obtained from the (SGC) with their analyst picks of P and S waves, which are then used for computing relative arrival times using cross-correlations of both P and S waves at

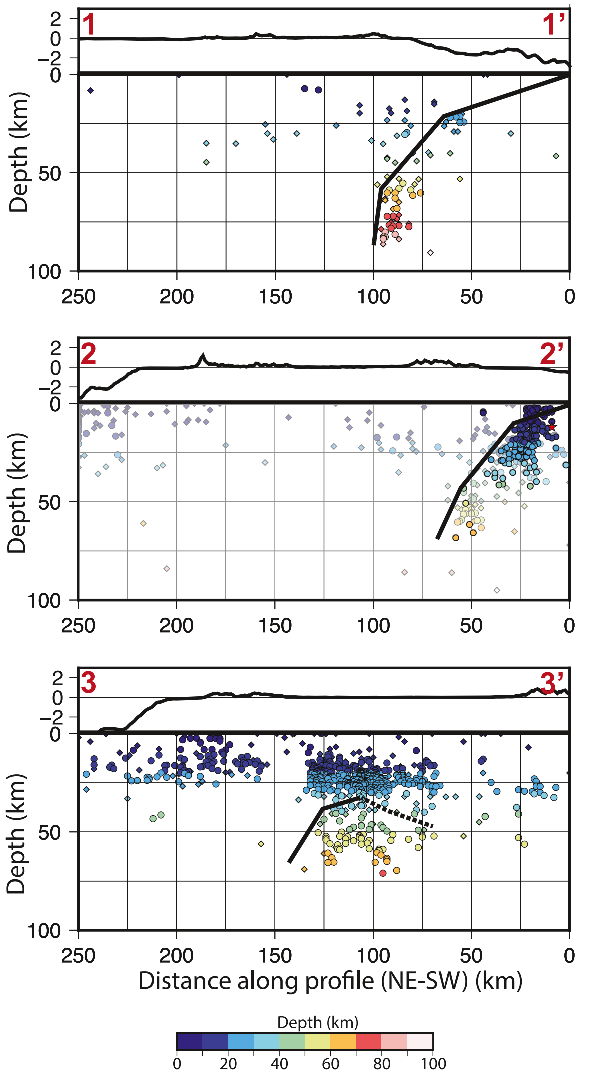

Figure 2. Seismicity Profiles. Symbols and colors are the same as in Figure 1. No vertical exaggeration. For each profile, the upper panel shows exaggerated topography for reference. In the lower panel for each profile, the solid black lines represent the upper limit of seismicity along the profile and is used for the calculation of slab length beneath the Panama Arc. The dotted black line shows the portion of the slab subducted originally beneath South America. The red star in Profile 2-2′ indicates the hypocenter of the 25 May 2025 Mw 6.5 event. Aftershocks are shown in the foreground on profile 2-2'. All other hypocenters are faded on that profile.

24 nearby stations from the Colombian and other countries or international seismic networks (Figure S5 in Supporting Information S1). The resulting catalog provides unprecedented resolution of the subduction interface seismicity in eastern Panama. Because the azimuthal coverage from the available stations is not ideal, we study the catalog's uncertainties by performing a delete-one jackknife error analysis (Prieto et al., 2007), running 100 instances of the entire catalog but with 50 earthquakes removed each turn. The resulting errors in the locations are shown in Figure S6 of Supporting Information S1, where we can see an average error of 1–2 km in the horizontal and 2–4 km in depth, with a few earthquake showing errors of up to 8 km in depth.

As shown in Figures 1 and 2, the aftershock sequence of the 25 May 2025 Mw 6.5 earthquake is probably the clearest evidence to date of southwestward dipping subduction (Figure S4 in Supporting Information S1). Figure 2 shows cross-sections from north (Profile 1-1′) to south (3-3′). The northernmost profile (1-1′) clearly shows a SW dipping subducting plate. The geometry highlighted by the seismicity suggests ∼140 km of subducted slab and is consistent with seismic reflection profiles showing shallow subduction along the plate boundary (Figure S6 in Supporting Information S1). The middle profile (2-2′) passes through the 25 May 2025 Mw 6.5 event, whose aftershocks delineate the downgoing plate geometry. Here, the geometry outlined by the seismicity suggests ∼100 km of subducted slab, somewhat less than along profile 1-1'. Our southernmost profile (Profile 3-3′) no longer crosses Caribbean Plate at the surface. However, we see clear evidence of the subducting Caribbean Plate at depth. This profile shows earthquakes below ∼30 km that dip both to the west and to the east. We see ∼40 km of subducted slab to the west the crest at 30 km depth. To the east, the seismicity dips less steeply and extends further, consistent with longer lived subduction beneath South America.

Combining our results with those of Camacho et al. (2010), we argue for a continuous SSW subducting slab of Caribbean Plate that extends at a minimum from the Canal Block in the west to the Gulf of Uraba in the east. The subduction profile identified by Camacho et al. (2010) lies just to the west of the apex of the Isthmus of Panama (orange line, Figure 1a), slightly to the west of the present study. Their profile defines the westernmost limit of where we feel confident identifying contiguous ongoing subduction, though we do not rule out subduction further to the west. The easternmost point of this subduction zone today defines the triple junction between the Caribbean Plate, the South American Plate and the Isthmus of Panama. Additional constraints are based on seismic reflection profiles (Goswami et al., 2019; Ramos, 2024) and gravity anomalies (Ramos et al., 2025) as can be observed in Figure S7 of Supporting Information S1. Figure S7 in Supporting Information S1 shows clear evidence of the Caribbean Plate subducting toward the SSW, with an accretionary wedge forming above the new plate boundary (Silver et al., 1990). The seismic profiles also show that the crustal thickness of the Caribbean plateau is around 15–20 km, consistent with previous work on the crustal thickness of the Caribbean Plate from refraction profiles (Barrera-Lopez et al., 2022), and 3D seismic reflection transects (Ramos et al., 2025).

3. Discussion

3.1. Proposed Tectonic History of the NPSZ

We propose a revised tectonic history of our study area based on the seismic evidence for subducted Caribbean Plate beneath the eastern portions of the Isthmus of Panama, and our observed decrease in the amount of slab subducted beneath the eastern flank of the Isthmus from north to south. Our proposed tectonic history relies

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heavily on previous plate reconstructions (Montes et al., 2019) with adjustments made at the time of subduction initiation.

The timing of subduction initiation is critical here, but difficult to ascertain with certainty. We calculate an estimated latest time of subduction initiation assuming orthogonal convergence along the nascent plate boundary that is consistent with the modern convergence rate between the Caribbean Plate and Isthmus of Panama (∼5.0 mm/yr, Jarrin et al. (2023)). Taking an average length of the observed Wadati-Benioff zone (∼100 km), we derive a minimum age of subduction initiation of ∼20 Ma. This is a minimum age because it assumes that all of the subducted Caribbean Plate is still seismically active and subduction that past convergence directions have remained constant. There are no tomographic studies in this area with sufficient resolution to look for any possible subducted plate below the observed seismicity. We also assign a maximum age of subduction initiation at ∼39 Ma based on the possibility of oblique convergence, cessation of arc volcanism and the cooling and sedimentation in blocks A and B (Montes, McFadden, et al., 2012).

Our proposed tectonic history is illustrated in Figure 3. Before 40 Ma, the Farallon plate subducted to the N-NE beneath the Caribbean plateau, forming a predominantly linear volcanic arc along the trailing edge of the Caribbean Plate (Panama arc, Figure 3a). Subduction of the Caribbean Plate beneath South America began at ∼58 Ma (Cardona et al., 2011, 2014) resulting in a substantial amount of Caribbean Plate emplaced beneath South America. Beginning at ∼39 Ma (Figures 3a and 3b) the arc began a phase of oroclinal bending (Montes, McFadden, et al., 2012; Rodriguez Parra et al., 2017), perhaps due to the initial collision of the easternmost end of the Choco Block (Block A) with the western margin of South America. It is possible that this initial collision and oroclinal deformation resulted in detachment of the arc from the Caribbean Plate shutting down magmatism east of the CFZ by ∼ 39 Ma (Figure 1). Blocks A, B and C may have been overthrusted above the detached Caribbean Plate in a WNW direction, roughly parallel to the Canal Fault Zone. Overthrusting of the arc would have removed the arc from the hydrated mantle wedge, and could explain the cessation of volcanism. If this occurred, then the first breaking of the Caribbean Plate that heralded this onset of SZI occurred at this time (Figure 3b).

Alternatively, it may be possible that some or all of the oroclinal bending could have been accommodated by the formation and shortening of the NPDB, whose timing and genesis is poorly constrained. Regardless, based on our minimum age, the Caribbean Plate north of the Panama arc must be fully broken and WSW dipping subduction initiated by at least 20 Ma (Figure 3c). This new plate boundary extended from, at a minimum, the western edge of the Canal Block to the eastern end of the Choco Block.

The formation of the NPSZ necessarily results in the formation of a new triple junction between the South American plate, the Caribbean Plate, and the Panama arc (star in Figure 3b). Once subduction initiated, this triple junction would migrate northward as the Choco Block progressively accreted onto South America from south to north. We hypothesize that beginning no later than 20 Ma, the eastern margin of the Panama arc begins to rotate clockwise toward the western margin of South America about an axis located at the northward moving new triple junction. The triangular shaped wedge of Caribbean Plate caught between the nascent NPSZ and the western margin of South America starts to be consumed bilaterally, as eastward subduction of the Caribbean Plate beneath South America continues (Figures 3c and 3d), and the new NPSZ to the west consumes some of the Caribbean Plate as well.

Given the inverted-triangle geometry of the southern Caribbean Plate at 20 Ma (Figure 3c), only a limited amount of Caribbean slab would have been subducted near the initial triple junction location. If, as we propose, the eastern flank of the Panama arc underwent continuous clockwise rotation around the northward-migrating triple junction, then a substantially larger portion of the Caribbean Plate would have been subducted beneath northern Panama than farther south. This is because the triangular shape of the Caribbean Plate resulted in a much greater distance to the north than to the south between Block B and the South American margin. This is consistent with the results derived from our seismicity profiles where the length of the subducted slab beneath Panama increases from south to north (Profiles 1 and 2, Figure 2). Particularly intriguing is our southernmost profile (Profile 3-3′, Figure 2). Here we interpret the top of the slab anticline to be located at ∼30 km depth, with the western flank extending to ∼70 km depth. That means that at the latitude of this profile, only ∼40 km of slab was subducted westward beneath Panama, significantly less than the 100 km observed in profile 2-2′ and 140 km in profile 1-1'. As blocks A and B are progressively attached to South America from south to north, the subducted plate beneath them becomes detached from the newly sutured continental lithosphere directly above it and is then only connected to

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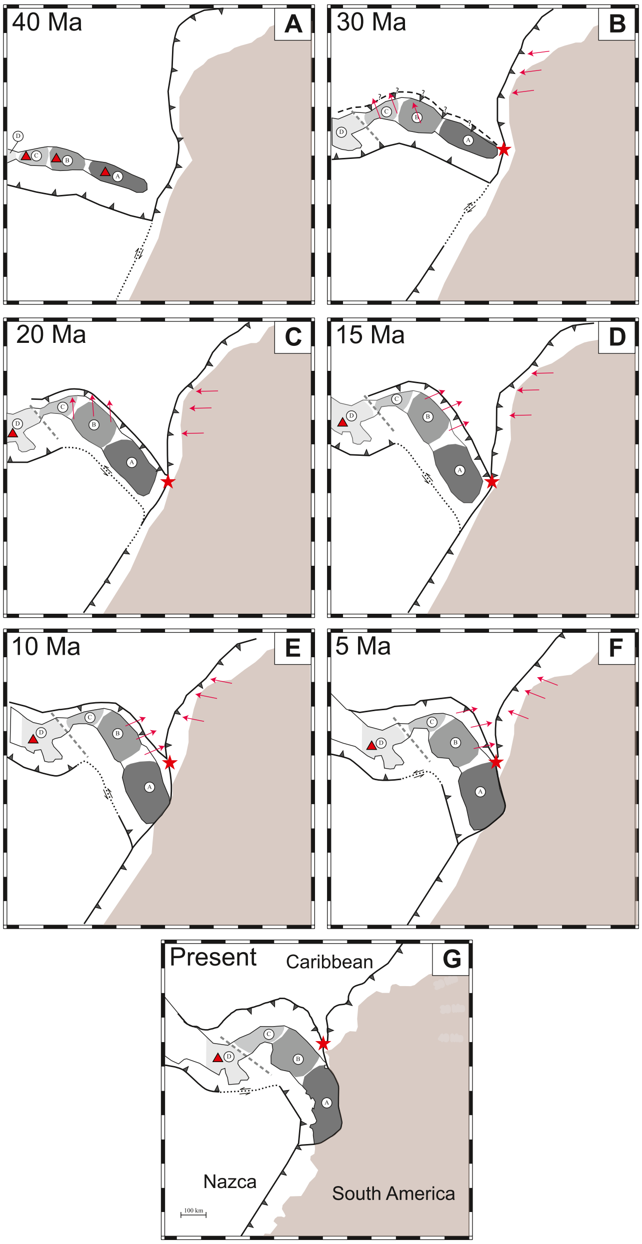

Figure 3. Tectonic evolution of the NPSZ. These are based on palinspastic reconstructions by Montes et al. (2019). Panels (a) through (g) show the relative locations of the Panama Arc and South America at 40, 30, 20, 15, 10, 5, and 0 Ma. The Panama Arc is divided in four microplates as shown in Figure 1. The red arrows in the different panels represent our interpreted relative motion between the Caribbean plate and South America and the Panama Arc and the Caribbean plate. The red triangles next to the letter for the blocks indicates whether volcanism was present in that block at that time. The new triple junction between the Panama Arc, the South American and the Caribbean plate is marked by the red star. Note how the triple junction moves relative to the Azuero block by about 250 km toward the north.

the surface by the not-yet subducted corner of the Caribbean Plate located north of the triple junction. It is this fully subducted corner of the Caribbean Plate that we observe in Profile 3-3'.

If correct, our proposed history implies that an accurate assessment of the timing of the detachment of the intraoceanic Panama arc from the Caribbean Plate requires a reassessment of paleo-plate-motions that includes the rotating eastern Panama/Choco block with a progressively northward-moving axis of rotation. This complex interplay affects the time- and latitude-dependent convergence rate between the Caribbean Plate and the Panama arc, which in turn limits our ability to accurately assess the timing of subduction initiation. More detailed modeling of the complexities of these geometries in the context of surrounding plates is needed but is beyond the scope of the present work.

3.2. The NPSZ as a Unique Subduction Initiation Event

To contextualize the NPSZ relative to other SZI events, it is necessary to review the different classification schemes that have been used to describe the diverse tectonic settings and forces that lead to SZI, as well as the stages undergone by nascent slabs leading up to the development of a mature self-sustaining subduction zone.

3.2.1. SZI Classification and Stages

The classic scheme for SZI defines them as either spontaneous (Cloetingh et al., 1982, 1989; Erickson, 1993) or induced (Stern, 2004; Stern & Bloomer, 1992; Stern & Gerya, 2018). Examples of spontaneous SZI include passive margin collapse and SZI along transform boundaries where one side of the boundary sinks beneath the other. Induced SZI examples include collision of a continent (or other buoyant body) into an existing subduction zone, resulting in either a change of subduction polarity ("polarity reversal") or a migration of the arc to the other side of the buoyant body ("transference"). Crameri et al. (2020) recast the terms spontaneous and induced as categories of forces (vertical and horizontal, respectively) that could lead to SZI, and define three types of SZI settings: newly destructive, episodic subduction, and polarity reversal. In newly destructive subduction zones, a previously unbroken plate breaks to create a new plate boundary. Episodic subduction is akin to transference in the classic schema, and polarity reversal is the same in both models. More recently, Lu et al. (2021) build on these concepts to define a 2 × 2 classification scheme for SZI archetypes. New subduction zones can be either internally- or externally-driven, and they can either have inherited plate weaknesses or new self-nucleated shear zones. Models with inherited plate weakness include episodic subduction (externally driven) and transform collapse (internally driven). Models that include self-nucleated shear zones include transference and polarity reversals (externally driven), as well as passive margin collapse and plume-induced subduction initiation (internally driven).

The development of a mature self-sustaining subduction zone is not instantaneous. It is a process that can take millions, potentially tens of millions of years. Agard et al. (2020) describe four steps to this process: (a) The initial subduction nucleation; (b) an early stage in which the plate boundary remains coupled and the slab struggles to progress; (c) an intermediate stage during which strain localization develops and the slab begins to sink readily; and (d) finally the integration of the subducted slab into mantle circulation ("slabitization"). These four steps correlate reasonably well with the four stages describe by Lallemand and Arcay (2021): incipient-diffuse;

incipient-localized; achieved; and self-sustained. The difference between the two models is that an achieved subduction (the third step of Lallemand and Arcay (2021)) requires the establishment of arc volcanism—a requirement not included in the third stage of Agard et al. (2020).

3.2.2. Where Does the NPSZ SZI Event Fit in?

The NPSZ initiation is difficult to classify using any of the aforementioned schemes. The Caribbean Plate was likely undeformed and not yet broken 40 Ma ago (Figure 3) while the Farallon plate subducted beneath it, forming the Panama arc. As early as 39 Ma, the Caribbean Plate may have been broken along the northern and eastern margins of the NPDB. To first order, then, the process could fit into a self-nucleated shear zone. By 20 Ma, we have SW oriented subduction of the Caribbean Plate. The change in subduction orientation, that is, from the N-NE dipping Farallon subduction to SW dipping Caribbean subduction might suggest SZI by polarity reversal. But in this case, the change in dip polarity is not induced by a clogging of the earlier subduction zone by the attempted subduction of a buoyant feature. Instead, it is the closing of the Caribbean Plate between Panama and South America that requires the consumption of the Caribbean Plate to accommodate that rotation (Figures 3c and 3d).

The NPSZ initiation may have been induced, at least in part, by differences in buoyancy between the younger, more-buoyant Panama arc versus the older thick Caribbean Plate onto which it was emplaced. Models associated with such density gradients have been proposed such as “relic arc” subduction initiation (Leng & Gurnis, 2015), passive margin subduction initiation (Stern, 2004), or lateral compositional density gradients (Niu, 2003). Along the NPSZ, we have subduction of thickened, albeit very old oceanic crust (i.e., the Caribbean plate) beneath even more thickened and somewhat rejuvenated oceanic crust (i.e., the Panama arc). Leng and Gurnis (2015) require a significant age difference between the two sides. In our case, the Caribbean Plate is ∼90 Ma (Dürkefälden et al., 2019; Sinton et al., 1998) and the arc is as young as 39 Ma (Montes et al., 2015), which is consistent with this model. However, Leng and Gurnis (2015)assume a pre-existing plate boundary separating the denser from the less dense blocks. We see no evidence for such a plate boundary prior to 39 Ma. The NPSZ is not technically a passive margin either (i.e., it is not the site of past continental rifting and formation of a new oceanic basin). It does, however, share many of the characteristics of passive margin in the context of SZI: the plate that is sinking is less buoyant than the overriding plate, even if only slightly, and it had an intact plate boundary prior to the onset of the forcing responsible for this SZI.

The maturity of the NPSZ can be assessed both in terms of the duration of subduction and evidence for subduction zone maturity. The NPSZ exhibits today a clear plate boundary, ongoing significant megathrust activity most recently demonstrated by the 25 May 2023 Mw 6.5 earthquake (i.e., strain localization [Agard et al., 2020])and a slab that reaches ∼100 km depth. According to Agard et al. (2020), these place the NPSZ in the intermediate stage, just prior to a fully mature subduction zone. There is no present-day arc yet associated with Caribbean subduction, either because the plate has yet to reach the depths at which point dehydration reactions can lead to mantle wedge metasomatism and flux melting, and/or because any such derived melts have yet to reach the shallow crust in sufficient volumes to generate new volcanoes (England et al., 2004; Ribeiro & Gerya, 2024; Ritter et al., 2024; Syracuse & Abers, 2006). Following Lallemand and Arcay (2021), the NPSZ would be in the incipient-localized stage because there is no volcanic arc, but the slab is clearly subducting.

4. Conclusions

We combine existing geological and new geophysical constraints to argue that the NPSZ represents a unique example of Cenozoic subduction initiation processes. Although subduction along the NPSZ is not yet self-sustained and no present-day arc volcanism is observed, the 25 May 2023 Mw 6.5 earthquake and its after-shocks along with our revised earthquake catalog show that subduction is an on-going process. Subduction most likely initiated 39–20 Ma and is driven by the rotation of the Panama arc clockwise toward the South American margin. The rotation was in turn initiated by the collision of the originally linear Panama arc with South America.

This subduction initiation process is unique, as it does not fit into existing SI models. It is not strictly a passive margin. It does not adhere to the concept of polarity reversal, because there was no clogging of the earlier subduction zone with a buoyant feature that forced the plate boundary reorganization. Density differences might help to explain the breaking of the Caribbean Plate and its subsequent subduction, but it seems unlikely that it would have done so had the Panama arc not begun to rotate onto the South America margin. The NPSZ represents thus an ideal example of a nascent subduction zone that deserves further attention to better understand what controls subduction initiation. In particular, it highlights the limitations of simple categorization schemes in areas with complex tectonic histories.

The NPSZ has significant implications for the tectonic history of this area, as well as the modern seismic and tsunami hazard throughout the Caribbean. Past M7+ events have been attributed to the NPSZ (Alvarado et al., 2017; Camacho & Víquez, 1993), and the 25 May 2023 Mw 6.5 event demonstrates the ongoing nature of this hazard. Although our work has been focused on the eastern flank of the NPSZ, there is growing evidence further to the west that the Caribbean may be subducting beneath Central America (Bourke et al., 2023). It is unclear at this time whether these two young subduction zones are connected, or whether a region of strike-slip motion may exist between them. More work is needed to fully evaluate this complex subduction zone and SZI event.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The relocated catalog developed by Dionicio et al (2025 in preparation) is available at 10.5281/zenodo.15214420 (Prieto & Dionicio, 2025). The hypoDD algorithm is available https://github.com/fwaldhauser/HypoDD. Waveforms used in relative arrival times can be downloaded at https://sismo.sgc.gov.co:8443/fdsnws. If needed by the reader, this website can be translated from Spanish using the translation extension in the reader's preferred browser.

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