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Plate convergence in the Indo-Pacific region*

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Abstract The Indo-Pacific convergence region is the best target to solve the two remaining challenges of the plate tectonics theory, i.e., subduction initiation and the driving force of plate tectonics. Recent studies proposed that the Izu-Bonin subduction initiation belongs to spontaneous initiation, which implies that it started from extension, followed by low angle subduction. Numerical geodynamic modeling suggests that the initiation of plate subduction likely occurred along a transform fault, which put the young spreading ridge in direct contact with old oceanic crust. This, however, does not explain the simultaneous subduction initiation in the west Pacific region in the Cenozoic. Namely, the subduction initiations in the Izu-Bonin-Mariana, the Aleutian, and the Tonga-Kermadec trenches are associated with oceanic crusts of different ages, yet they occurred at roughly the same time, suggesting that they were all triggered by a major change in the Pacific plate. Moreover, low angle subduction induces compression rather than extension, which requires external compression forces. Given that the famous Hawaiian-Emperor bending occurred roughly at the same time with the onset of westward subductions in the west Pacific, we propose that these Cenozoic subductions were initiated by the steering of the Pacific plate, which are classified as induced initiation. Induced subduction initiation usually occurs in young ocean basins, forming single-track subduction. The closures of Neo-Tethys Oceans were likely triggered by plumes in the south, forming northward subductions. Interestingly, the Indian plate kept on moving northward more than 50 Ma after the collision between the Indian and Eurasian continents and the break-off of the subducted oceanic slab attached to it. This strongly suggests that slab pull is not the main driving force of plate tectonics, whereas slab sliding is.

Keyword: plate tectonics; subduction initiation; drifting history; Pacific plate; Indian plate; slab sliding

1 INTRODUCTION

Plate tectonics is taken as one of the four most important achievements in natural sciences in the 20th century, alongside with the quantum mechanics, the relativity theory, and the DNA double helix theory. However, more than 50 years after the theory has been proposed (McKenzie and Parker, 1967; Morgan, 1968), it is still controversial as regard to the driving force of plate tectonics (Forsyth and Uyeda, 1975; Bott, 1991; Bokelmann, 2002; Billen, 2008; van Summeren et al., 2012; Sun, 2019) and the mechanism that initiated plate subduction (Stern, 2004; Sun, 2017, 2019; Stern and Gerya, 2018; Arculus et al., 2019; Li et al., 2019). Plate convergence results in volcanic eruptions, earthquakes, formation of ore deposits, strait closures/openings and climate changes. It is therefore a hot topic in Earth Sciences (Engen et al., 2008; Wang et al., 2011; Sun et al., 2012; Brierley and Fedorov, 2016; Gao and Wang, 2017; Scambelluri et al., 2017; Liu et al., 2020; Zhang et al., 2020).

The Indo-Pacific region includes the West Pacific

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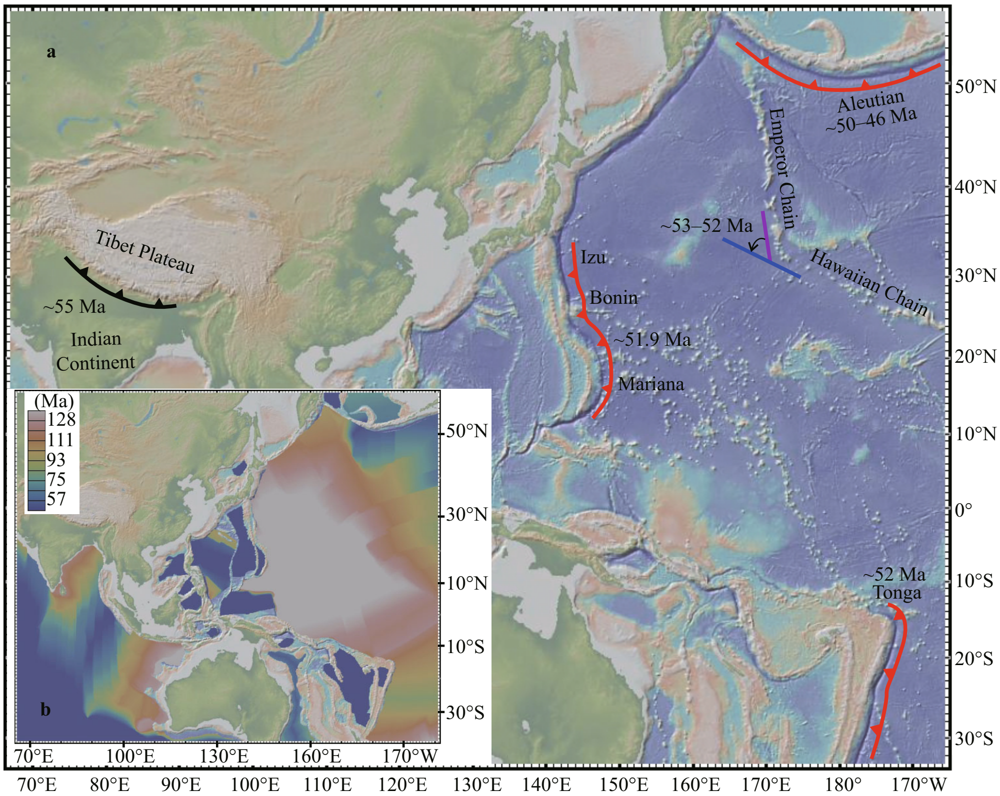

Fig.1 Topographic map of the Indo-Pacific region

a. the change of the Pacific drifting direction and subduction initiation events in west Pacific; b. the ocean crust age of the Indo-Pacific region. The Hawaiian-Emperor bend record the time of the Pacific Plate motion change at ~52 Ma (O'Connor et al., 2015); The collision between Indian and Asia was at ~55 Ma (Zheng and Wu, 2018; Zhu et al., 2015); Ages for subduction initiation: Izu-Bonin-Mariana (Reagan et al., 2019), Tonga (Meffre et al., 2012), and Aleutian (Jicha et al., 2006; Layer et al., 2007; Vaes et al., 2019). Base map and ocean crust age are from GeoMapApp (http://www.geomapapp.org/).

Ocean, the East Indian Ocean and islands and marginal seas in between. It consists of thousands of islands and a series of convergent margins, including subduction zones of the Pacific plate, e.g., Izu-Bonin-Mariana subduction zone, and the Indo-Australian plate, e.g., the Sunda-Banda subduction zone, and subduction zones of a variety of small ocean basins, e.g., the Nankai, the Philippines, the Manila subduction zones, etc (Fig.1). These convergent margins with different ages and subduction stages in this region provide the best place to study subduction initiation and the driving force of plate tectonics.

In this contribution, we summarize the drifting history of the Pacific and Indian plates and discuss mechanisms that caused subduction initiation and the closure of the Neo-Tethys Ocean.

2 DRIFTING HISTORY OF THE PACIFIC PLATE

The drifting history of the Pacific plate is still controversial. Reconstruction based on magnetic anomalies using GPlates suggested that the spreading ridge between the Pacific and the Izanagi plates was roughly parallel to the current subduction zone as indicated by the Japanese lineation in the West Pacific (Seton et al., 2012) (Fig.2). It was further speculated that this spreading ridge was subducted ~55–50 Ma ago (Müller et al., 2008; Seton et al., 2012).

The parallel subduction of a young spreading ridge is usually associated with flat subduction and a diagnostic adakite belt along the subduction zone, followed by A-type granite. Parallel ridge subduction results in compression and uplifting, similar to the east Pacific convergent margins. The west Pacific convergent margins, however, have been dominated by extension and backarc basins, rather than compression and mountain chains. Moreover, no linearly distributed adakite of ~55–50 Ma, parallel to the subduction zone, was reported in Japan, Korea, and eastern China. Instead, Early Cretaceous adakite belts perpendicular to the subduction zone have been identified (Fig.2), e.g., the Lower Changjiang (Yangtze) River belt (~140±10 Ma) (Mao et al., 2006; Ling et al., 2009; Li et al., 2010; Sun et al., 2010; Xie et al., 2011, 2019; Wang et al., 2016), the Xuhuai-Shandong region (~130±5 Ma) (Ling et al., 2013; Sun

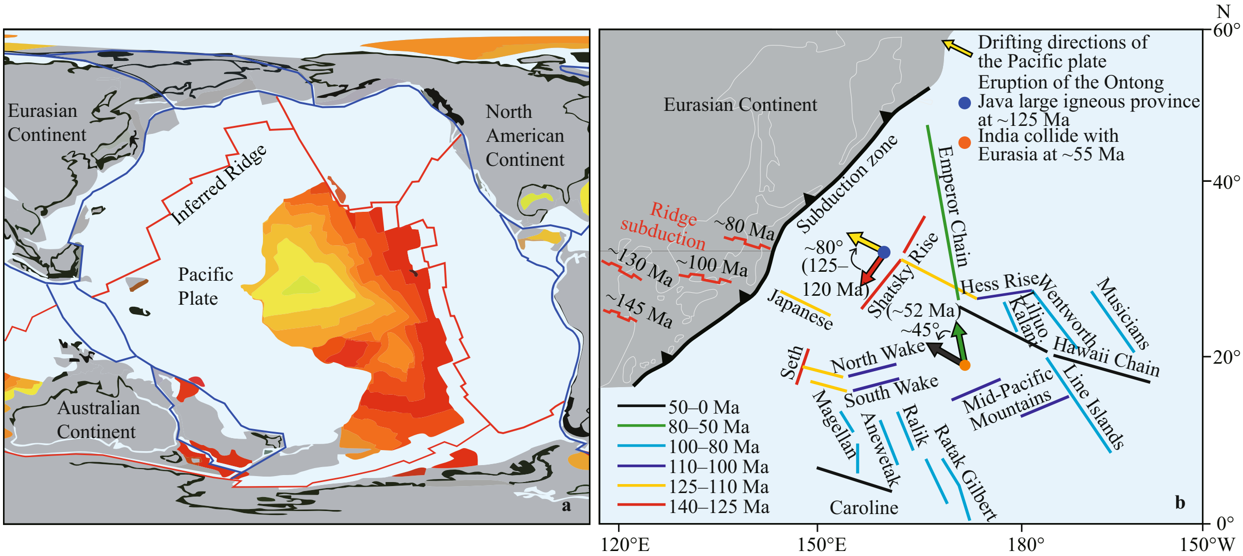

Fig.2 The Pacific Plate reconstruction at ~70 Ma using GPlates based on paleomagnetic data (a) (Seton et al., 2012); the reconstruction of the drift history of the Pacific Plate using island chains in Pacific and the geological records of eastern China (b) (Kinoshita, 1995; Sun et al., 2007, 2010, 2012, 2017; Ling et al., 2009, 2013; Wu et al., 2017)

et al., 2019). Both adakite belts are accompanied by abundant later A-type granites (Yu et al., 2008; Li et al., 2012, 2014; Xie et al., 2012; Zhou et al., 2012; Jiang et al., 2018a, b, c). These strongly suggest that the ridge between the Pacific and the Izanagi plates were roughly perpendicular to the subduction zone, and it continuously moved northwards (Fig.2). This is further supported by the spatial and temporal distribution of Cretaceous alkalic basalts in the North China Craton, which suggests northwestward subduction of ridge followed by slab rollback at ~110 Ma (Wu et al., 2017). Consistently, there is a Late Cretaceous granite belt in the Median Tectonic Line, Southwest Japan, which is parallel to the subduction zone (Kinoshita, 1995). The age of the magmatic rocks decreases from ~95±5 Ma in the southwest to 65±2 Ma in the northeast, which indicates the migration of the ridge between the Pacific and Izanagi plates (Kinoshita, 1995). All these argue against the reconstruction of Seton et al. (2012).

In addition to magnetic anomalies, seamount chains are also useful for plate reconstruction (Wilson, 1963; Wessel and Kroenke, 1997; Koppers et al., 2001; Sharp and Clague, 2006). There are dozens of seamount/island chains in the Pacific plate, which indicate three major changes in the drifting direction of the Pacific plate (Sun et al., 2007). The drifting direction of the Pacific plate changed from southwestward to northwestward at ~125 Ma, which is approximately consistent with the eruption of the Ontong Java large igneous province (Fig.2; Parkinson et al., 2001; Tejada et al., 2002). It then moved roughly westward between 110–100 Ma, followed by northward migration until ~53–52 Ma (O'Connor et al., 2015). These do not fit the popular model of reconstruction (Seton et al., 2012), either.

The spreading ridge is usually perpendicular, not parallel, to the drifting direction. The Pacific plate was drifting roughly northward between ~100–52 Ma. If the spreading ridge between the Pacific and the Izanagi plates was parallel to the current subduction zone, it intersects with the drifting direction of the Pacific plate. This requires one limb of the ridge subducting underneath the other. Geodynamically, this is very unlikely. There is no observation supporting such a scenario, either.

Such discrepancy is likely due to the rotation of the Pacific plate at ~125 Ma (Sun et al., 2007). There are two components during the steering of the Pacific plate, radical direction change and rotation. The rotation component was not considered in any previous reconstructions. Moreover, in the modeling of Seton et al. (2012), the Pacific plate was "switched to a fixed Pacific hotspot reference frame for the Pacific plate" before 83.5 Ma (Seton et al., 2012). This assumption is unrealistic.

3 DRIFTING HISTORY OF THE INDIAN PLATE

The Indian plate was separated from the Antarctic continent at ~130 Ma due to the eruption of a large igneous province represented by the Kerguelen

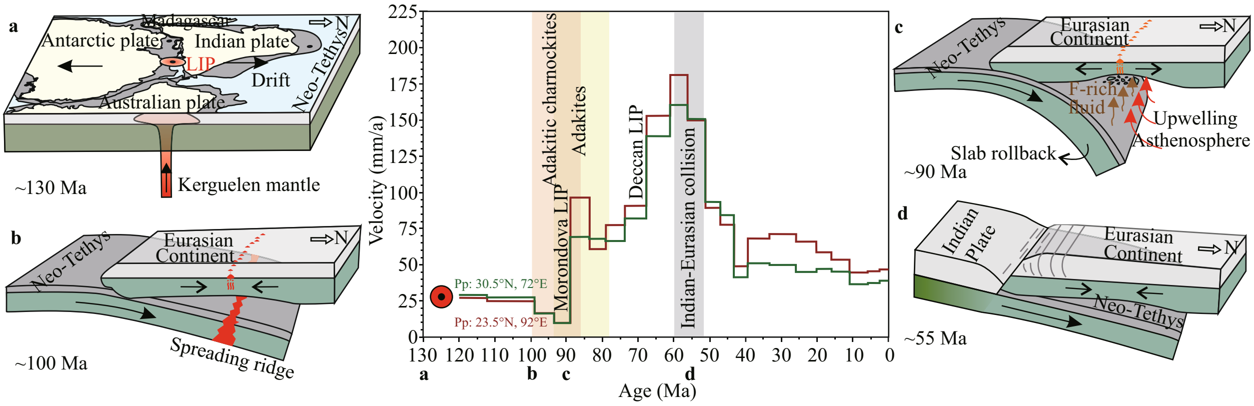

Fig.3 The northward drift rate of the Indian Plate (Van Hinsbergen et al., 2011) and geological events

a. the eruption of the Kerguelen plume triggered the initial northward drift of the Indian Plate (Gaina et al., 2007; Chatterjee et al., 2013); b. the subduction of the Neo-Tethys ridge slow down the drift rate of the Indian Plate (Zhang et al., 2017b; Sun et al., 2018); c. the rollback of the subducted Neo-Tethys Plate accelerates the Indian Plate (Zhang et al., 2017a, 2018, 2019; Sun et al., 2018); d. the collision between the Indian Plate and Eurasia continent slows down the drift rate of the subducted Indian Plate (Zhu et al., 2015; Zheng and Wu, 2018).

Islands (Gaina et al., 2007; Chatterjee et al., 2013). Before the collision between the Indian and the Eurasia continents, the opening of the Indian Ocean in the south was coupled with the northward subduction and closure of the Neo-Tethys Ocean in the north (Wang et al., 2008; Wu et al., 2010; Ding et al., 2017; Sun et al., 2018; Sun, 2019).

The northward drifting rate of the Indian Plate changed dramatically (Fig.3) (Van Hinsbergen et al., 2011; Sun et al., 2018). It was slow at the beginning, at a rate of ~25 mm/a, which dropped slightly at ~110 Ma, and then decreased to ~15 mm/a at ~100 Ma. Interestingly, the drifting rate of the Indian plate dropped to ~10 mm/a at ~90±3 Ma, when the Morondova large igneous province erupted (Torsvik et al., 2000; Bardintzeff et al., 2010). In general, the eruption of large igneous province accelerates plate drifting. The slowing down of the Indian Plate is attributed to the subduction of the Neo-Tethys spreading ridge underneath the Gangdese belt, southern Tibetan Plateau (Sun et al., 2018), which is indicated by adakites and other high-temperature rocks (Wen et al., 2008; Zhang et al., 2010; Sun et al., 2018). This suggests that the ridge subduction generated major resisting forces, larger than the additional pushes from the Morondova plume. Remarkably, the northward drifting of the Indian plate was accelerated to ~100 mm/a at ~88 Ma, which is coincident with the youngest adakitic charnockite. Charnokite is a special kind of rock with very high formation temperature, whereas adakite usually forms through partial melting of the subducted young oceanic slab. Adakitic charnokite indicates the final stage of ridge subduction, i.e., the commencement of slab rollback. Numerical modeling suggests that this is likely due to the onset of slab rollback, and consequently the release of resistance from ridge subduction (Sun et al., 2018). The drifting rate of the Indian plate was further increased to >150 mm/a at ~65 Ma, when the Deccan large igneous province erupted (Van Hinsbergen et al., 2011).

An increasing number of studies suggest that the Indian continent collided with the Eurasian continent at ~60 Ma (Wang et al., 2008; Copley et al., 2010; Ding et al., 2017; Najman et al., 2017; Zheng and Wu, 2018). This, however, is not shown in the drifting rate, which increased further to ~200 mm/a at 60 Ma and then dropped a little at ~55 Ma (Fig.3). This suggests that the early collision was a soft collision, which may have carried down more sediments that have accumulated at the passive continental margin. The increased amount of sediments carried down along the subduction channel may have lowered the friction due to lubrication (Sobolev and Brown, 2019), such that the Indian plate was further accelerated. The drifting rate of the Indian plate dropped to ~150 mm/a at ~55 Ma, followed by a rapid decrease at ~50 Ma, suggesting the commencement of the hard collision. There is a slow period at ~43–40 Ma, which is coincident with the peak of alkalic basalt activities in the Tibetan Plateau (Chung et al., 1998; Liang et al., 2006; Wang et al., 2010). This is likely due to the breakoff of the oceanic crust attached to the subducting Indian continent.

Remarkably, the Indian Plate has been moving continuously northward at a rate of ~40 mm/a since ~40 Ma, after the continental collision and the breakoff of the subducted oceanic crust attached to it.

This strongly suggests that slab pull is not the main driving force of plate tectonics. Instead, the big slope from the spreading ridges to the collision zone is responsible for the northward drifting of the Indian Plate (Sun, 2019).

Subduction is continuing in the Southeast Asia. One may argue that the northward drifting of the Indian Plate was driven by the subduction plate in the Southeast Asia. This does not work for two reasons. First, the Southeast Asia subduction is connected to the Australian Plate, whereas the Indian Plate is separated from the Australia Plate by the Ninetyeast Ridge. Second, in case the driving force comes from the Southeast Asia, there should be a rotation in the Indian Plate, which is not seen, either.

4 PLATE SUBDUCTION INITIATION IN THE WEST PACIFIC REGION

One remaining problem for plate tectonics is how plate subduction is initiated (McKenzie, 1977; Davies, 1995; Niu et al., 2003; Stern, 2004; Niu, 2016; Sun, 2017, 2019; Stern and Gerya, 2018; Zhou et al., 2018; Arculus et al., 2019; Li et al., 2019). There are many subduction zones initiated in the Cenozoic in the West Pacific convergent margin, making it the best location to study subduction initiation. The International Ocean Discovery Program (IODP) carried out 4 expeditions across the Izu-Bonin-Mariana (Expeditions 350, 351, 352) (Tamura et al., 2014; Arculus et al., 2015; Pearce et al., 2015) and the Tonga-Kermadec convergent margins (Expedition 371) in the West Pacific (Sutherland et al., 2018), aiming at better understanding on subduction initiation. However, the debate as regard to subduction initiation is still unresolved, yet.

Previous authors proposed that large mantle plumes were the initiator of plate tectonics before tectonic system ever appeared (Campbell and Griffiths, 1990; Sun, 2019). Large mantle plumes may cause kilometer scales of uplifting of the overriding plate. Consequently, the overriding plate is titled, sliding away from the center of the plume (Campbell and Griffiths, 1990).

Given that slab sliding is the main force that drives plate tectonics (Sun, 2019), once the plate tectonics started, it can be self-sustained. New oceanic basins forms with old oceanic basins disappear. This again requires subduction initiations. Two types of subduction initiation within the plate tectonic regime have been proposed, spontaneous and induced (Stern, 2004; Gerya et al., 2015; Stern and Gerya, 2018). Spontaneous initiation refers to gravitational instability of oceanic lithosphere and is required to launch the modern regime of plate tectonics; induced initiation refers to continuing plate convergence following jamming of a subduction zone by buoyant crust (Stern, 2004). In a recent paper, these two types of subduction initiation are refined: Induced subduction initiation occurs when pre-existing plate convergence causes a new subduction zone to form, whereas spontaneous subduction initiation occurs without pre-existing plate motion when large lateral density contrasts occur across profound lithospheric weaknesses of various origin (Stern and Gerya, 2018).

Numerical geodynamic modeling suggests that a spreading ridge separated by a transform fault provide the best candidate for subduction initiation. The spreading ridge is young and less dense, which is in direct contact with old and dense oceanic crust along the transform fault. The large density contrast causes extensions due to the sink of the old oceanic crust, which is favorable for spontaneous subduction initiation (Zhou et al., 2018). According to the modeling, the larger the transform fault is, the more the density contrast. Consequently, the old plate starts to subduct at the ridge-transform fault junction, which then laterally propagates along the transform fault, developing into a mature subduction zone (Zhou et al., 2018). In addition, the lithosphere at the ridge is much thinner than the old oceanic crust, such that it is easier to be obducted.

The Pacific Plate to the east of the Izu-Bonin-Mariana convergent margin is mostly Jurassic, which was over 100 Ma old when the westward subduction started at ~52 Ma (Ishizuka et al., 2011, 2018; Li et al., 2019; Reagan et al., 2019). There was no young spreading ridge in the nearby region within the West Pacific Plate (Sun et al., 2007). Some plate reconstruction models indeed proposed that there was a spreading ridge in the west Pacific parallel to the current subduction zone until ~50 Ma (Seton et al., 2012). This reconstruction was based on an assumption that the Pacific Plate did not move relative the plume systems in the Pacific Ocean before 83.5 Ma (Seton et al., 2012), which is clearly not the case as indicated by seamount chains (Sun et al., 2007) and geologic evidence in eastern China (Ling et al., 2013; Wu et al., 2017). They did not consider the rotation of the Pacific Plate in the Cretaceous, either. Moreover, this proposed spreading ridge was roughly parallel to the subduction zone, which is not favorable for the initiation of westward subduction.

The Pacific Plate changed its drift direction from roughly northward since ~100 Ma (Sun et al., 2007) to northwestward at ~53–52 Ma (O'Connor et al., 2015), with a northwestward subducting spreading ridge (Ling et al., 2013; Wu et al., 2017). The northward drifting of the Pacific Plate should have formed a large transform fault. Even though there was no spreading ridge near the Izu-Bonin-Mariana region within the Pacific Plate, the northward subduction of the Neo-Tethys Plate have formed a series of backarc basins, including the proto-South China Sea (Sun, 2016) and the Philippine Sea (Lee and Lawver, 1995). The young ridge needed for the initiation of the westward subduction in the West Pacific (Zhou et al., 2018) could be the backarc spreading center in the Philippine Sea, if there was indeed such tectonic settings. This ridge was located to the south of the Izu-Bonin-Mariana trench. However, no age propagation along the subduction zone has been identified. Therefore, the detailed process of subduction initiation in the Izu-Bonin-Mariana remains elusive.

Subduction initiated by density contrast is characterized by extension. Interestingly, a recent geochemical study on forearc basalt and boninite samples collected during the Bonin forearc drilling expedition (IODP Expedition 352) show that forearc basalts from the drill hole are not enriched in elements that are mobile during plate subduction (Reagan et al., 2019). Meanwhile, their isotope signatures show the affinity of the Indian Ocean mantle. In contrast, early boninites are enriched in both fluid mobile elements and high field-strength elements. The isotopic signatures indicate a transition from the Indian Ocean to the Pacific Ocean mantle sources, which may be plausibly explained by contributions from melting of altered oceanic crust, without contributions from subducted sediments (Li et al., 2019). This is best explained by that sediments were scraped off due to subduction erosion at the early stage of plate subduction because of low subduction angles (Li et al., 2019; Reagan et al., 2019). In this case, the subduction initiation requires a westward push, which contradicts with extensions, and thus is different from pure spontaneous subduction initiation (Sun, 2019).

Note, there is strong evidence for Pacific-wide synchronicity in terms of subduction initiation: the oldest forearc volcanic rocks from Tonga-Kermadec Island was ~52–48 Ma (Meffre et al., 2012), and magnetic anomaly interpretation shows that the Tasman Sea basin ceased spreading at ~52–50 Ma (Gaina et al., 1998). These subduction zones are associated with oceanic crusts of different ages (Fig.1). It is hard to imagine that spontaneous subduction initiation occurred at the same time in all these places.

New dating results suggest that the bending of the Hawaiian-Emperor trends occurred at ~53–52 Ma (O'Connor et al., 2015). This is simultaneous with the formation of the oldest boninite in the Izu-Bonin convergent margin (Reagan et al., 2019), suggesting that the subduction initiations in the west Pacific region was resulted from the steering of the Pacific Plate.

The Pacific Plate was drifting northward before the bending (Fig.2) (Seton et al., 2012; Sun et al., 2007). The original subduction zone was located to the north of the Aleutian Islands, in the Berling Sea. The bending indicates that the northward subduction of the Pacific Plate was blocked, likely by an oceanic plateau.

There are two big oceanic plateaus in the Berling Sea, the Shirshov and the Bower Ridges. There were probably also other plateaus, which have been merged into the east Eurasia continent (Niu, 2016). It is likely that the Shirshov ridge and/or a disappeared plateau have contributed to the steering of the Pacific Plate.

Consistently, the oldest Aleutian Islands early-arc basalt so far reported is ~50–46 Ma (Jicha et al., 2006; Layer et al., 2007; Vaes et al., 2019), which is considerably younger than other arc volcanic rocks, suggesting different tectonic setting compared to the west Pacific. We argue that the Cenozoic initiations of Pacific Plate subduction was induced by the steering of the Pacific Plate marked by the famous Hawaiian-Emperor bending (Fig.1).

5 CONCLUSION

The initiations of major Cenozoic subduction zones in the West Pacific are all related to the steering of the Pacific Plate recorded by the Hawaiian-Emperor bending. Therefore, they are all induced subduction initiations.

The closures of Neo-Tethys Oceans were related to induce subduction initiation, which were likely triggered by plumes in the south.

The northward drifting of the Indian Plate continued more than 50 Ma after the collision between the Indian and Eurasian continents, suggesting that slab pull is not the main driving force of plate tectonics.

6 DATA AVAILABILITY STATEMENT

All data generated and/or analyzed during this study are available from the corresponding author upon reasonable request.

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