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The Rotation of the Pacific Plate Induced by the Ontong Java Large Igneous Province

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ABSTRACT: The eruption of large igneous provinces usually has major geodynamic influences on overriding plates. Seamount chains indicate that the drifting direction of the Pacific Plate changed by ~80° in the Early Cretaceous when the Ontong Java Plateau formed. This, however, is not fully consistent with the magnetic anomalies. Here we show that there is an angle of ~25° between the magnetic anomaly lines M_0 and 34 of both the Japanese and the Hawaiian lineations, suggesting that the orientations of both spreading ridges changed by roughly the same angle towards the same direction. The configurations of the Shatsky Rise, the Papanin Ridge and the Osbourn Trough suggest that the eruption of the Ontong Java plume head uplifted the southeastern corner of the Pacific Plate, and pushed its east part northward by ~700 km within 2 Ma. Meanwhile, the west part of the Pacific Plate was subducting southwestward underneath the eastern Asian Continent. These two forces together rotated the Pacific Plate anticlockwisely by ca 50°. Consequently, the drifting direction of the Pacific Plate also changed from southwestward to northwestward, which plausibly explains the ca 80° bending of the Shatsky Rise and the Papanin Ridge. The ridge between the Pacific and the Izanagi/Kula plates was pointed towards the ~300° orientation, whereas the Pacific Plate was subducting towards the ~250° orientation before ~125 Ma, and towards ~280° afterward.
KEY WORDS: Pacific Plate, Ontong Java Plateau, rotation, magnetic anomalies, Shatsky Rise, geodynamics.

0 INTRODUCTION

The eruption of a large igneous province (LIP) is usually very destructive. It uplifts and even breaks the overriding plate, changes the drifting direction of associated plates, and may have significant environmental impact that can cause mass extinctions (Sun, 2019; Courtillot and Olson, 2007; Sun et al., 2007; Campbell, 2005; Xu et al., 2004; Griffiths and Campbell, 1991). The Ontong Java Plateau is one of the largest LIPs so far recognized (Taylor, 2006; Coffin and Eldholm, 1993). Previous studies on seamount chains proposed that its eruption changed the drifting direction of the Pacific Plate by ~80° from southwestward to northwestward (Sun et al., 2007), which is best shown by the distributions of the Shatsky and the Ojin rises and the bending of the Papanin Ridge (Fig. 1). Unfortunately, the detailed process of such a major change is not fully compatible with the magnetic anomalies (Fig. 2).

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1 THE ROTATION OF THE PACIFIC PLATE

The Ontong Java LIP erupted at ~119 – 125 Ma (Taylor, 2006; Tejada et al., 2002) near M_0 (~125.93 Ma), which was followed by the Cretaceous Superchron (125.93 – 83.64 Ma) (Gee and Kent, 2007) that has no geomagnetic reversal for ~42 Ma. Interestingly, the magnetic anomaly lines, M_0 (125.93 Ma) and 34 (83.64 Ma) of the Hawaiian Lineation, are not parallel to each other, but with an angle of ~25°, such that the Cretaceous Superchron crust forms a big triangle on the northwest Pacific Plate. The width in the north end of this triangle is more than 2 000 km. Remarkably, the angle between M_0 and 34 of the Japanese Lineations is also ~25° (Fig. 2). Both angles are much smaller than the bending angle of seamount chains (~80°) (Fig. 1).

Magnetic anomaly lines M_0 and 34 represent the orientations of the spreading ridges before and after the Cretaceous Superchron, respectively. The angle between M_0 and 34 indicates that the orientations of the two spreading ridges rotated during this period. In general, the orientation of a spreading ridge is defined mainly by the relative movements of the paired plates. Plate rotation is the most efficient way to change the orientation of a spreading ridge.

The Japanese Lineation records the spreading between the Pacific and the Izanagi/Kula plates, whereas the Hawaiian Lineation represents the spreading between the Pacific and the

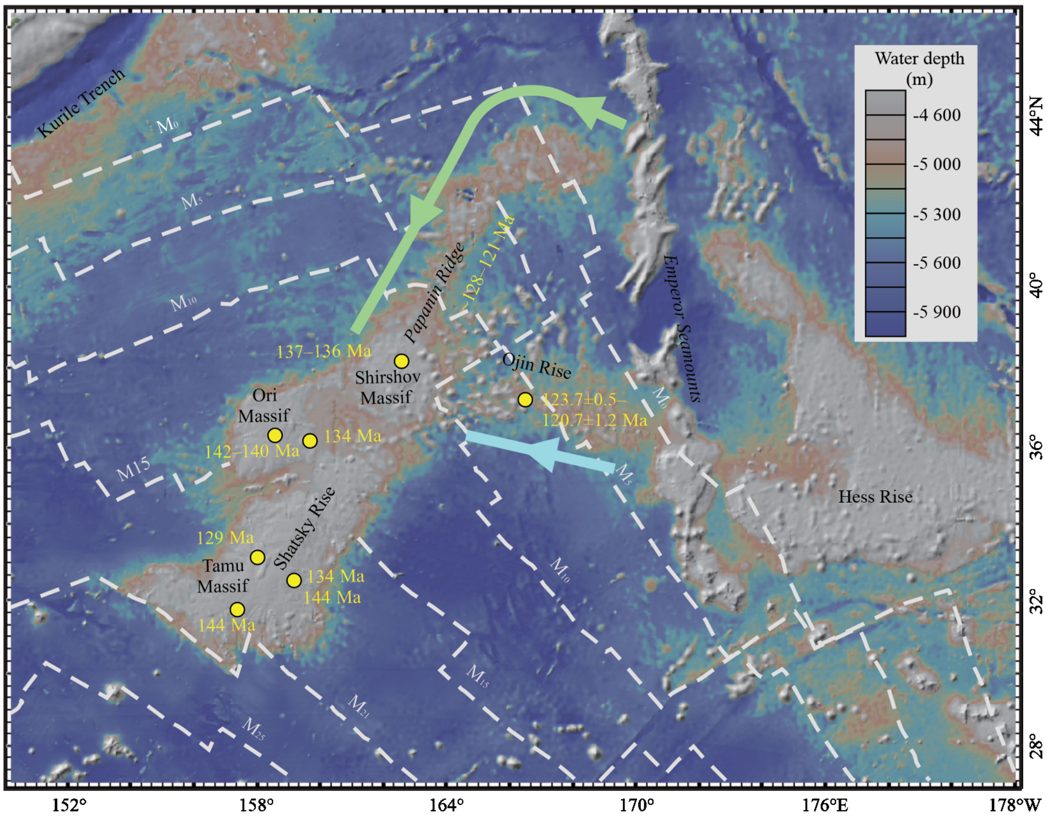

Figure 1. Magnetic anomalies and seamount ages around the Shatsky Rise (Tejada et al., 2016; Sager et al., 2005). The age progression suggests that the Pacific Plate was drifting southwestward. The Shatsky Rise is connected to the Papanian Ridge and the Ojin Rise. Significantly, the Papanin Ridge is curved in the Early Cretaceous, and then lost connections to any other seaount chains. The age of the Papanian Ridge is not well constrained. However, based on the magnetic anomalies, we estimated that the bending occurred at ~125 Ma, as a result of the rotation of the Pacific Plate induced by the eruption of the Ontong Java LIP (Sun et al., 2007; Taylor, 2006; Tejada et al., 2002). The ages of the Ojin range from 123.7–120.7 Ma (Sano et al., 2020). The base map is from GeoMapAPP.

Farallon plates. Note, the angles between M_0 and 34 are roughly the same for both the Hawaiian and the Japanese lineations, ~25° (Fig. 2), suggesting that either the Pacific Plate rotated anticlockwise by ~50°, while the other two did not change, or the Pacific Plate remained stationary whilst the other two plates both rotated clockwisely by ~50° (Fig. 3).

It is not easy to rotate and/or change the drifting direction of a big plate, but it is far more difficult for two plates to rotate and coordinate so well that the spreading ridges changed exactly the same degrees at the same time. Therefore, we propose that the Pacific Plate rotated anticlockwise by ~50° relative to the Kula and the Farallon plates, whereas the other two plates did not rotate much.

This rotation occurred roughly simultaneously with the Ontong Java LIP. Previous studies suggested that the eruption of the Ontong Java LIP changed the drifting direction of the Pacific Plate by ~80° (Sun et al., 2007). The magnetic anomalies suggest that the eruption of the Ontong Java LIP was also responsible to for the anticlockwise rotation of the Pacific Plate. It is likely that the eruption of the Ontong Java plume head has resulted in rapid rotation and northwestward tilting of the Pacific Plate, which pushed the Pacific Plate northwestward. These changes are best recorded by the Shatsky Rise and the Papanin Ridge.

In fact, it is difficult for the Ontong Java plume head to influence only the Pacific Plate, leaving other plates untouched. In contrast to the Kula and the Farallon plates, the Izanagi Plate was connected directly to the Pacific Plate along the Cretaceous Superchron Triangle in the northwest corner of the Pacific Plate (Fig. 2). The fast rotation of the Pacific Plate may have changed the drifting of the Izanagi Plate. The problem is that the Hawaiian Lineation is located all on the East Pacific Plate. No magnetic anomalies after the Cretaceous Superchron have been identified in the northwest corner of the Pacific Plate.

2 DISCUSSION

Geochemical studies show that the Meiji and Detroit seamounts erupted on the fossil ridge between the Pacific and the Izanagi plates, followed by plume-ridge interactions (Sun et al., 2021; Regelous et al., 2003). The northward migration of the fossil ridge, carrying the Hawaiian-Emperor plume with it, formed the famous Emperor seamount chain (Sun et al., 2021). Therefore, the Meiji and Detroit seamounts marked the position of the ridge (Sun et al., 2021). Note, the fossil ridge is not parallel to the magnetic anomaly 31 of the Hawaiian Lineation. Instead, the angle between M_0 and the ridge is ~60° (Fig. 2). This is likely because of the ridge jump associated with the rotation of the Pacific Plate (Norton et al., 2007; Heller et al., 1996). After the ridge jump, the Izanagi and Kula plates were separated into two plates.

Magnetic anomalies suggest that the Shatsky Rise and the Papanin Ridge were erupted near a triple-junction at ~144–126 Ma (Sager et al., 2019; Nakanishi et al., 2015) (Fig. 1). The

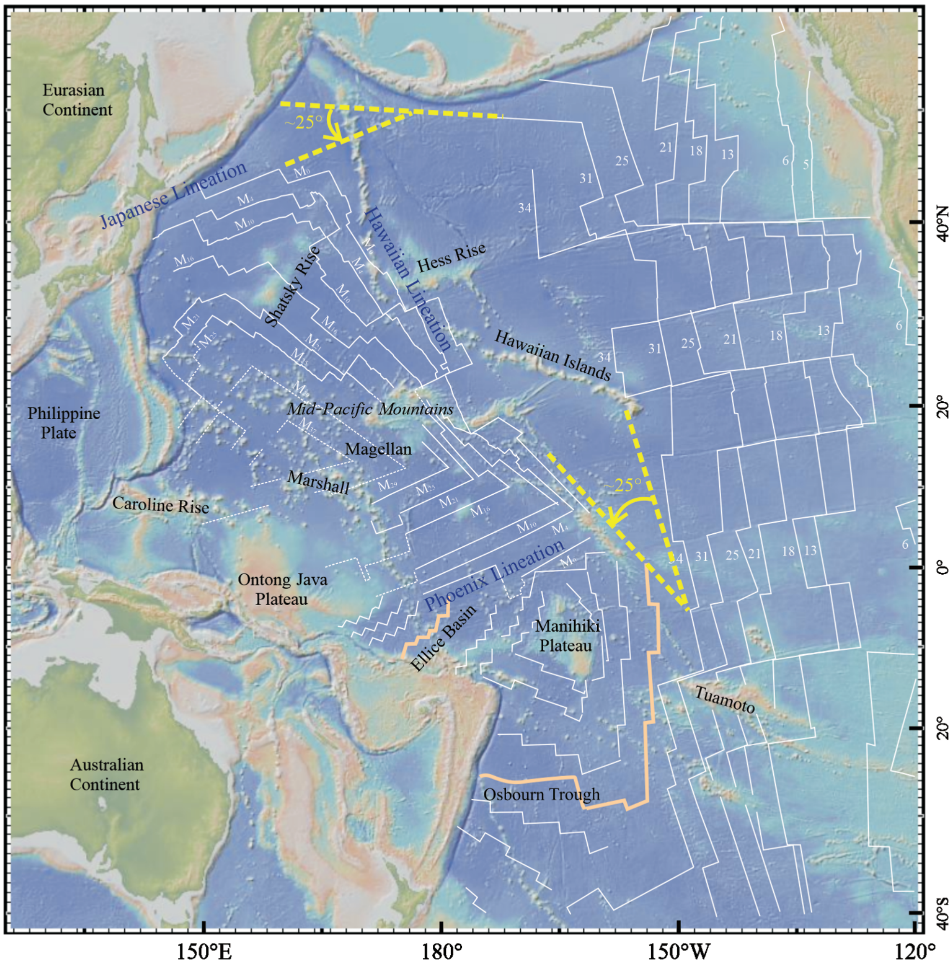

Figure 2. Magnetic anomalies in the Northwest Pacific Plate. Note, anomaly lines M_0 and 34 of both the Japanese and the Hawaiian lineations are not parallel to each other. The angles between these magnetic anomaly lines are both 25°. Previous studies attributed these angles to the rotation of the ridges between the Pacific and the Izanagi and the Farallon plates (Seton et al., 2012). Ridges, however, do not rotate by themselves. It was the Pacific Plate that rotated. Data source: GeoMapApp and reference (Seton et al., 2012). Rotation is also recorded in the Ellice Basin (Benyshek et al., 2019).

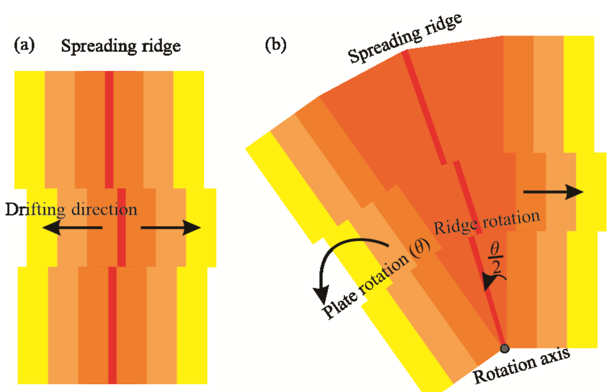

Figure 3. The relation between an oceanic plate and the associated spreading ridge during rotation. During the rotation of an oceanic plate, the newly formed oceanic crust distributes evenly on both sides of the spreading ridge. Therefore, when an oceanic plate rotates by θ degrees, the ridge should have rotated by $\theta/2$.

Papanin Ridge is bent at its north end, followed by a magmatic gap. The end of the Papanin Ridge is more than 500 km away from and, ~15 Ma older than the Hess Plateau. One explanation is that the Papanin Ridge was connected to the Hess Plateau (Tejada et al., 2016). However, the drifting rate of the Pacific Plate was >10 cm/yr, which would corresponds to a distance of >1 500 km in 15 Ma. This means that the distance between the Papanin Ridge and the Hess Plateau is too short. Alternatively, the rotation of the Pacific Plate resulted in a ridge jump. Consequently, the younger seamounts of the Papanin Ridge erupted on the Farallon Plate, which was subducted in the Late Cretaceous under the North American Continent (Liu et al., 2010). We propose that the Papanin Ridge may be connected to the Ojin Rise before the ridge jump.

Interestingly, the bending of the Papanin Ridge is curved, which is consistent with an anticlockwise rotation with the axle in the south. Previous studies estimated that the Papanin Ridge formed between 128 and 121 Ma (Tejada et al., 2016), with large errors. The Papanian Ridge erupted near a triple junction (Sager et al., 2019; Nakanishi et al., 2015). Therefore, the age should be fairly close to that of the magnetic anomalies. The bending of the Papanin Ridge is right next to the M_0, suggesting that it occurred shortly after ~125.93 Ma, which gives the lower limit of the age.

The Pacific Plate was drifting southwestward before the eruption of the Ontong Java LIP as indicated by the Shatsky

Rise (Fig. 1) (Sun et al., 2007). The arrival of the LIP lifted the southeast corner of the Pacific Plate and pushed it northwestward (Sun, 2019; Sun et al., 2007). Meanwhile, the Pacific Plate was subducting southwestward underneath the eastern Asian continent in the west, as indicated by the distributions of granites and ore deposits (Yan et al., 2021; Zhang et al., 2017; Li et al., 2014; Sun et al., 2012; Wang et al., 2011). Namely, the east end of the Pacific Plate moved northwards, while its west end was moved southwestwards. Consequently, the Pacific Plate rotated anticlockwise quickly, with its rotation axle in the south.

In principle, the northwestward movement of the Pacific Plate followed roughly along the tangent line of the rotation. This is shown by the Shatsky and the Ojin rises (Fig. 1). The Ojin Rise is parallel to the tail of the Papanin Ridge and erupted between 124–121 Ma (Sano et al., 2020). There are clear spatial and temporal gaps between the Skatsky and Ojin rises. Considering the decollation of the Papanin Ridge and the extensions along the Osbourn Trough, we propose that the Ojin Rise is the succession of the Papanin Ridge.

Due to the eruption of the Ontong Java LIP, the eastern end of the Pacific Plate drifted rapidly northwards. Consequently, the tail of the Papanin Ridge was “chopped off”, and the plume formed the Ojin Rise to the south. The distance between the tail of the Papanin Ridge and the Ojin Rise is ~700 km. The oldest seamount of the Ojin Rise is about 2 Ma younger than the youngest age of the Papanin Ridge. This corresponds to a drifting rate of ~35 cm/yr during this 2 Ma period, which is marginally faster than previous estimation of ~10–25 cm/yr in the Cretaceous Superchron (Maruyama et al., 1997). Note, the Ojin Rise is fairly straight, suggesting that the Pacific Plate was settled rapidly and drifted northwestward after ~124 Ma.

Previous geodynamic laboratory simulation experiments showed that the eruption of a plume head may cause kilometer scale uplift and even the breakup of the overriding plate (Campbell, 2005; Griffiths and Campbell, 1991). Such uplift has been well illustrated in the Emeishan LIP (Xu et al., 2004). The eruption of the giant Ontong Java and the Manihiki plateaus should also have uplifted the southeastern corner of the Pacific Plate in a kilometer scale and lubricated the lithosphere-asthenosphere boundary through melting, which could have resulted in the rotation of the Pacific Plate.

During the eruption of the plume head, large amounts of magmas could be ponded underneath the lithosphere, forming a big magma “mushroom” (Griffiths and Campbell, 1991; Campbell and Griffiths, 1990). The total volume of the Ontong Java and the Manihiki plateaus together is estimated to be more than 60 million cubic kilometers (Ingle and Coffin, 2004). Given that only a small portion (within ~20%) of the plume head erupted (Campbell, 2007), there should be about 50 million cubic kilometers of magmas underneath the Ontong Java and Manihiki plateaus. Assuming that the magma “mushroom” associated with the Ontong Java Plateau was ~2 000–4 000 km in diameter, and the average thickness of the mushroom disc was ~15 to 60 km. Because basaltic magmas are ~20% lighter than mantle peridotite, the ponding of a such a large volume of basaltic magmas alone can result in uplifts of a large area of the Pacific Plate (~2 000–4 000 km in diameter) by ~3–12 km. Based on plate reconstruction, the Ontong Java Plateau was several thousand kilometers away from the subduction zone (Seton et al., 2012). The uplift of such a large plate at the southeast corner produces an additional northwestward push of ~5 to 20 TN/m, which was responsible to for the breakup and tilting of the Pacific Plate. It would also dramatically lower the viscosity, which is favorable for the fast rotation and the change in drifting direction of the Pacific Plate.

As discussed above, the anticlockwise rotation of the Pacific Plate finished within 2 Ma after the eruption of the Ontong Java LIP. Taking the 50° anticlockwise rotation out of the 80° angle between the Skatsky and Ojin rises, the drifting direction of the Pacific Plate actually changed clockwise by ~30° (Fig. 1).

The Japanese Lineation M_0 is currently pointing towards the 250° orientation. Considering the rotation of 50°, the ridge between the Pacific and the Izanagi/Kula plates was pointed towards an ~300° orientation before ~125 Ma. This is roughly the same direction as the fossil ridge between the Pacific and the Izanagi plates indicated by the Meiji and Detroit seamounts, ~310° (Sun et al., 2021).

The orientation of the Ojin Rise is now northwestward, directing towards ~280°, whereas the Pacific Plate has no further major rotation after the Cretaceous Superchron. Therefore, the Pacific Plate has been subducting towards the northwest, ~280°, after the rotation commenced at ~125 Ma (Fig. 1). If we take all the ~80° bending at the Shatsky Rise as a result of translational motion as previously did (Sun et al., 2007), then the Pacific Plate should have been subducting towards ~200°, which is roughly parallel to the subduction zone. In this contribution, we find that 50° of the bending came from the rotation, such that the translational change was ~30° . Therefore, the Pacific Plate was subducting towards ~250°.

The subduction of the Pacific Plate had a major influence on the geologic evolution of eastern China (Zhang Z Z et al., 2021; Zhu and Sun, 2021; Zhang Z K et al., 2020a, b; Wu et al., 2019; Zheng et al., 2018; Zhu et al., 2015;Sun et al., 2013, 2012; Wang et al., 2011; Xu et al., 2009; Li and Li, 2007; Zhou and Li, 2000). The subduction direction suggested by this study is consistent with the spatial and temporal distribution of magmatic rocks and different types of ore deposits in southeastern China (Yan et al., 2021; Zhang et al., 2017; Chen et al., 2016; Wang et al., 2011). Meanwhile, the refined orientation of the spreading ridge between the Pacific Plate and the Izanagi Plate is consistent with the distribution of adakite and Cu deposits and other traces of ridge subduction along the Lower Yangtze River belt (Liu et al., 2021; Zhang S et al., 2021; Jiang et al., 2020; Xie et al., 2020; Jiang et al., 2018; Li et al., 2012; Ling et al., 2009) and, to a lesser extent, the Xuhuai region (Sun et al., 2019; Ling et al., 2013) and the Shandong Peninsula as well as basalts in the North China Craton (Wu et al., 2017; Li et al., 2014).

The rotation of the Pacific Plate should also be recorded in the Phoenix Lineation. This is not as clear as the other two lineations. One reason is that the Phoenix Lineation has been severely modified/destroyed by the eruption of the Ontong Java Plateau and plate subduction. The magnetic anomalies of the Phoenix Lineation are not continuous to the south and the west of the Ontong Java Plateau, with the Caroline Ridge, the Ellice Basin, the Manihiki Plateau and the Osbourn Trough distributed between M_0 and 34 (Fig. 2). Nevertheless, there is a

15° rotation in the Ellice Basin (Benyshek et al., 2019). Although M_0–M_{29} can be identified to the east of the plateau, the connection between M_0 and 34 is not clear, likely because of a ridge jump (Müller et al., 2008).

The Manihiki Plateau erupted at the same time as the Ontong Java Plateau (Taylor, 2006). They are now separated by the Ellice Basin. Previous studies suggest that the Ontong Java Plateau, including the Manihiki Plateau, was erupted near the Phoenix spreading ridge (Taylor, 2006). In this case, it is likely that the Phoenix Ridge was located in the Ellice Basin. However, the M_0 of the Phoenix Lineation is not parallel with, but points towards, the fossil spreading ridge of the Ellice Basin, suggesting that the spreading center may have jumped to the Osbourn Trough shortly after the plume eruption.

The Osbourn Trough is an oxbow shaped fossil spreading center located both to the south and to the east of the Manihiki Plateau, i.e., it is kinked around the Manihiki Plateau at the southeast corner of the Pacific Plate (Fig. 2). The spreading along the Osbourn Trough started shortly after M_0 and ceased at ~83.5 Ma (Zhang and Li, 2016), implying its connection to the eruption of the Ontong Java Plateau, which pushed the Pacific Plate northwards and to a lesser extent, westward. After ~83.5 Ma, the ridge jumped southward. The total spreading of the south limb of the Osbourn Trough adds up to ~3 000 km, whereas that of the east limb, ~1 000 km (Fig. 2). This is consistent with the rotation and the superfast drifting of the Pacific Plate during this period (Maruyama et al., 1997).

3 IMPLICATIONS TO PLATE RECONSTRUCTION

The rotation of the Pacific Plate induced by the eruption of the Ontong Java Plateau is critical for plate reconstruction. Almost all previous models did not consider the rotation of the Pacific Plate. Therefore, it was proposed that the ridge between the Pacific and the Izanagi plates was roughly parallel to the current subduction zone as recorded by the Japanese Lineation (Fig. 4) and was subducted parallelly to the trench at ~51 Ma (Seton et al., 2012), which is roughly the time of the Cenozoic subduction initiation in the West Pacific (Li et al., 2021; Maunder et al., 2020; Sun et al., 2020a, b; Sutherland et al., 2020; Reagan et al., 2019; O'Connor et al., 2015). This geodynamic mechanism is very difficult. It is not supported by geologic observations in the eastern Eurasian Continent. The Cenozoic northwestward subduction initiation of the Pacific Plate was coincident with the hard collision between Australian/Indian and Eurasian continents, strongly suggesting that the subduction initiation resulted from the collision along the Neo- Tethys orogen (Sun et al., 2020).

Ridge subduction forms adakite and A-type granites, instead of forearc basalts and boninites associated with subduction initiations (Ling et al., 2009; Yogodzinski et al., 1994). The abundant Cenozoic forearc basalt and boninite widely distributed in the West Pacific, e. g., in the Izu-Bonin arc (Li H et al., 2021; Li H Y et al., 2019) and the lack of adakite during subduction initiation (~ 49–52 Ma) (Li et al., 2021) do not support such a ridge subduction (Wu and Wu, 2019; Seton et al., 2012).

More importantly, magnetic anomalies show that the Pacific Plate was drifting essential northwards between ~100 – 50 Ma (Fig. 5), i.e., the Pacific Plate was not subducting westward (Mao et al., 2011; Sun et al., 2007). If the ridge between the Pacific and the Izanagi plates was roughly parallel to the subduction zone,

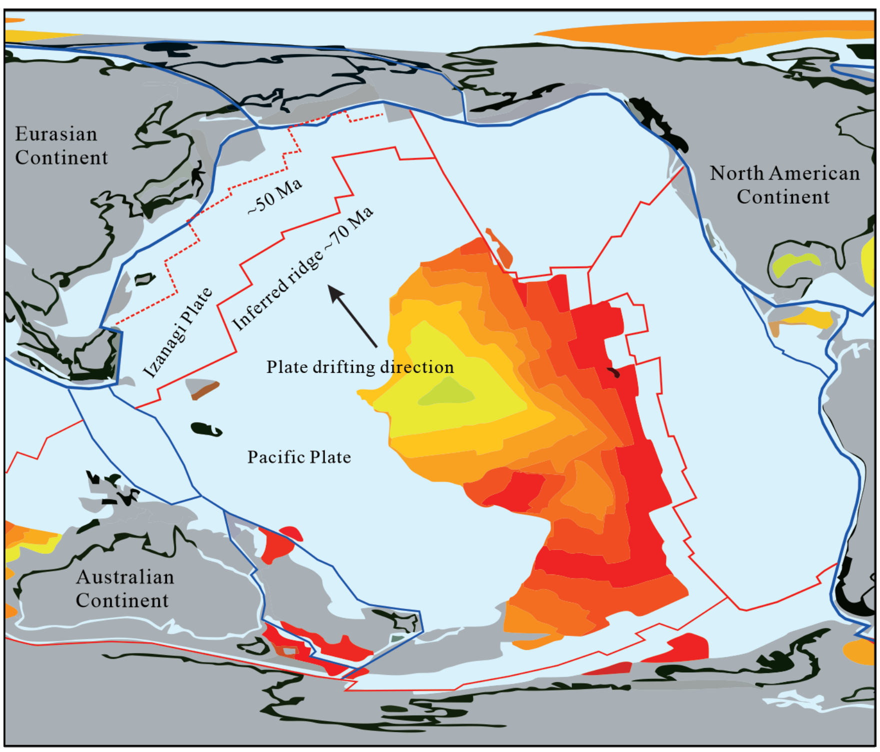

Figure 4. Plate reconstruction using GPlates by previous authors (Seton et al., 2012). This reconstruction did not consider the rotation of the Pacific Plate. It suggests that the ridge between the Pacific and the Izanagi plates was parallelly subducted underneath the eastern Eurasian continent. In this case, there should be abundant adakites parallelly distributed along the subduction zone. This is not observed.

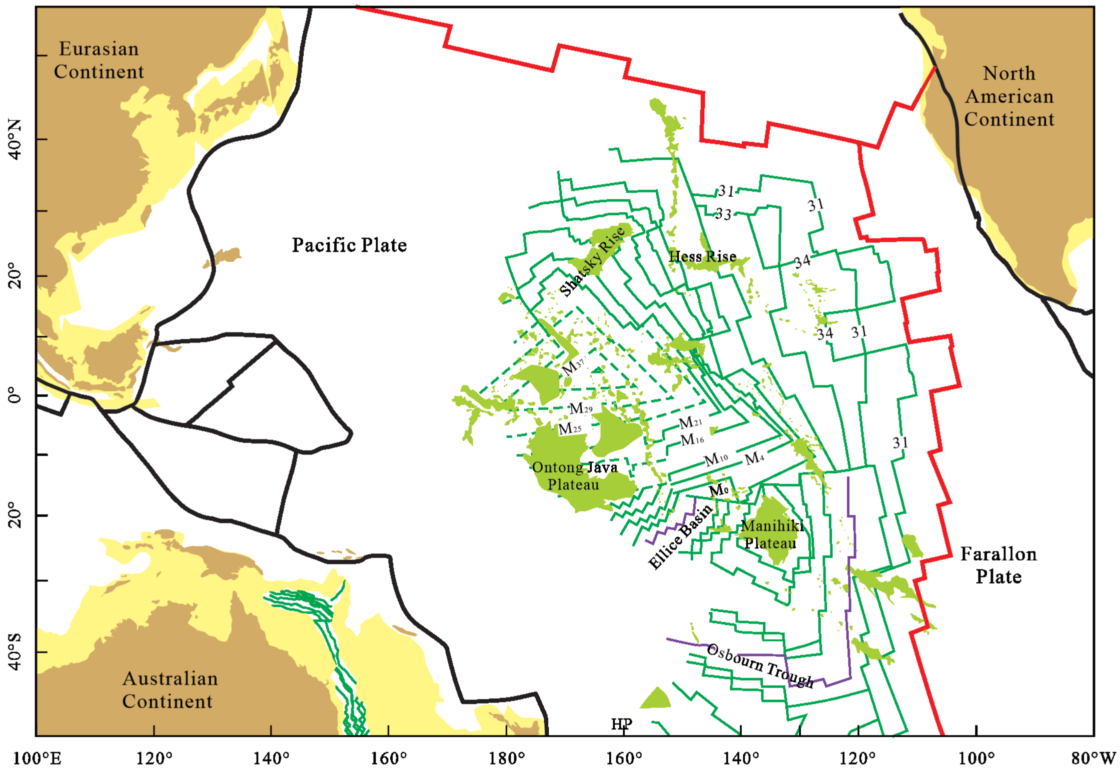

Figure 5. The reconstruction of the Pacific Plate at 50 Ma. The ridge between the Pacific and the Izanagi plates was nearly vertically subducted underneath the eastern Eurasian continent. Its location is determined based on magnetic anomalies, the plume-ridge interaction of the Hawaiian plume (Sun et al., 2021) and the geological records in the eastern Eurasian continent (Wu et al., 2017; Kinoshita, 1995).

then the drifting direction of the Pacific Plate should have been roughly parallel to the ridge. In this case, it is not a ridge, but a transform fault. There should not be any magnetic anomalies.

Mantle plume is the igniter of plate tectonics (Sun, 2019). A large plume head may uplift and break the overriding plate, resulting in new spreading and new ocean basins. It may also rotate associated plates, which should be considered carefully in plate reconstruction.

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