Reconstruction of the Pacific plate: Constraints from ocean floor and eastern China

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PUBLIC SUMMARY

- The drift direction of the Pacific plate has changed many times.
- Magnetic anomalies show rotations of the Pacific and the Izanagi plates.
- The Ontong Java mantle plume induced rotation of the Pacific Ocean.
- The drifting history of the Pacific plate agrees well with the geological records of eastern China.
Magnetic anomalies show that the Pacific plate rotated counterclockwise by ~50°, induced by the eruption of the Ontong Java Plateau at ~125 Ma. Meanwhile, the drifting direction of the Pacific plate also changed from southward (~265°) to northward (~300°). The rotation promoted the destruction of the North China Craton (NCC) and induced slab rollback, which was responsible for the Cretaceous large-scale magmatism and mineralization in eastern China. Correspondingly, the orientation of the spreading ridge between the Pacific and Izanagi plates has also changed, which was originally towards ~290° before 125 Ma. Such a configuration is consistent with Late Mesozoic geologic events in eastern China. The spatiotemporal distribution of magmatic rocks and ore deposits suggests that the Pacific plate began to subduct southwestward underneath southeastern China in the Early Jurassic (~175 Ma), and reached the Nanling Mountains. In contrast, the Izanagi Plate was still connected to the NCC before ~170 Ma. Its northwestern drift before/during subduction initiation resulted in compression that wedged the NCC into the East Asian continent and resulted in fold belts in three directions in weak zones surrounding the NCC and strike-slip faults along the south and the north margins (known as Event A of the Yanshanian Movement [165-170 Ma]). This is followed by extension during slab rollback. The Izanagi plate rotated clockwise by ~50° between 149.35 Ma and 140.42 Ma, which was coincident with commencement of Event B of the Yanshanian Movement, both of which resulted from the collision between a micro-continent on the Izanagi plate and eastern China.

INTRODUCTION

It is generally well accepted that the drifting and subduction of the Pacific and the Izanagi (also known as Paleo-Pacific) plates have controlled the major tectonic events in the East Asian continent since the Jurassic, e.g., the Yanshanian Movement, the destruction of the North China Craton (NCC) and large scale mineralization.17-22 However, the reconstruction of the Pacific plate motion is controversial.10,12,21 A currently well accepted reconstruction scheme of the Pacific plate13,22 cannot explain the completely different geologic evolution in the South and the North China Blocks and the Yangtze River Belt in the Late Jurassic and the Early Cretaceous. To reconcile those competing reconstruction models, it is crucial to re-evaluate the various means of reconstruction and to remove circular reasoning,24 and more importantly, provide additional constraints from the Pacific plate and the East Eurasian continent. In this contribution, we reconstructed the Pacific plate based on distribution of seamount chains, magnetic anomalies and the geologic evolution in eastern China since the Jurassic.

DRIFT OF THE PACIFIC PLATE AS SHOWN BY SEAMOUNT CHAINS

Seamount chains were one of the first types of evidence that show spreading ocean floors. During World War II, Hess discovered ~160 flat-topped seamounts between Hawaii and the west coast of the Pacific Ocean, which was explained correctly, as drowned ancient islands, named Guayots.26 Since then, seamount chains have been used to demonstrate the drifting history of oceanic plates. For example, the famous Hawaiian-Emperor bend was plausibly explained by a change in drifting direction of the Pacific plate above a stationary “hot spot” (Figure 1),27 which is a milestone of both the plate tectonics theory and the plume hypothesis.27 Therefore, seamount chains are widely used for plate reconstruction.26-33

Plate reconstruction using seamount chains is quite straightforward for plates that have not experienced subduction, although it is not always accurate due to plume-ridge and/or plume-plume interactions.34-39 Nevertheless, seamount chains provide good constraints on changes in drifting directions.17,26,33 This is particularly useful for the reconstruction of the Pacific plate, which has been subducting since the Jurassic at least,17,40-41 and more for the Izanagi plate which has been totally subducted.42-43

Seamount chains indicate that the Pacific plate has changed its drift direction several times since the Early Cretaceous (Figure 1). It was drifting southwestward before ~125 Ma as illustrated by the Shatsky Rise. The southwest end of the Shatsky Rise erupted at ~147 Ma44-47 and is bent at the northeast end of the Paparin Ridge at ~125 Ma, which lost connections to any other seamount chains.46-47 This is likely attributed to a ridge jump during the rotation of the Pacific plate, such that younger seamounts of the Paparin Ridge erupted on the Farallon plate, and then subducted underneath the North American continent.46-47 The distribution of the Ojin Rise shows that the Pacific plate drifted towards ~300° after ~124 Ma (Figure 2).

At 110 Ma, the Pacific plate drifted southwestward again for several million years (Figure 1). This is coincident with the subduction of the Neo-Tethys ridges48-51 and the transition from Pacific to Indian tectonic regimes in the Philippines.52-54 It is likely that ridge subduction hindered the northwestward movement of the western Pacific plate.

After 100 Ma, the Pacific plate moved north-northwestward, forming a series of seamount chains, including the Musicians, the Wentworth, the Line seamounts, the Louisville and the Emperor seamount chains. It is worth mentioning that many of the above mentioned chains did not last long enough to record a complete history between 100-52 Ma (Figure 1).55 The Louisville and the Emperor seamount chains are the two longest chains that recorded the bending at ~52 Ma. Interestingly, the bending of Louisville seamount chain is much less pronounced than that of the Emperor-Hawaiian seamount chain.53-56 This is because the Emperor-Hawaiian plume was carried northward by the drifting fossil ridge between the Pacific and Izanagi plates.53

The ages of seamounts at the Emperor-Hawaiian bending range from 47.9 Ma at Kimmie (age of post shield basalt)48 to 47.4 Ma at Yuryaku and 47.5 Ma at Daikakuji (Figure 3),34-37 which are ~ 47 Ma is well accepted as the time of the bending. However, the eruption of a seamount in the Hawaiian-Emperor chain usually lasts several million years. In particular, the age of Yuryaku ranges from 31.6 Ma to 47.4 Ma.57 The Hawaiian-Emperor seamounts usually consist of three stages of eruptions, alkali basalt, shield basalt and rejuvenal alkali basalt. It is not easy to confine the eruption stage of a dredged sample. Nevertheless, early alkali basalts are usually covered by shield basalts, such that dredged alkali basalts are likely rejuvenal, which are usually several million years later than the shield basalts. Therefore, these ages might be younger than the commencement of the bending. Nevertheless, new results suggest that the Pacific plate changed its drifting direction at ~52 Ma, forming the famous Hawaiian-Emperor bend as shown by the Musicians Ridges (Figure 1),37 which is coincident with the commencement of the subduction initiation of the Cenozoic plate subduction in the Izu-Bonin-Mariana trench within error (52 Ma).58-59 and marginally later than the hard collision along the Neo-Tethys suture (53 Ma).60 Nevertheless, the spatiotemporal distribution of seamounts suggests that the Pacific plate drifted very slowly between 52-47 Ma around the bending.
time. This is consistent with the fact that the subduction initiation along the Izu-Bonin-Mariana trench took several million years. The ages of forearc basalts in the Izu-Bonin-Mariana convergent margin range from 52 to 49 Ma. The oldest Cenozoic arc volcanic rock in Kyushu-Palau Ridge, the oldest arc of the Izu-Bonin-Mariana convergent margin system, so far reported, is 47 Ma. This suggests that the Cenozoic subduction initiation in the West Pacific took several millions years and finally commenced sometime slightly before ~47 Ma.

Significantly, the northward drifting of the Australian plate also dropped quickly between ~53-50 Ma, reached essentially zero at ~50-46 Ma, and then bounced back (Figure 4). It is likely that the northward subduction of the Australian plate was blocked by an island/microcontinent. After the commencement of the northwestward subduction of the Pacific plate, a new northward subduction of the Australian plate also started.

**LATE MESOZOIC GEOLOGIC EVENTS IN EASTERN CHINA**

Given that large proportions of the Pacific plate have been subducted and vanished, geologic records in surrounding regions are particularly useful for the reconstruction of the Pacific plate. The distribution of convergent margin magmatic rocks, ore deposits, and traces of ridge subductions all provide constraints on the drifting/subduction directions of the Izanagi and Pacific plates, and the spatiotemporal distribution of the ridge between these plates.
two plates.

Significantly, the geologic evolution of eastern China continent from the Late Jurassic to the Early Cretaceous varied significantly from the south to the north. For example, abundant Late Jurassic magmatism and mineralization developed in the South China Block (~175 to 145 Ma); Linearly distributed magmatism and mineralization along the Lower Yangtze River Belt (LYRB) occurred mainly in the Early Cretaceous (~140±10 Ma). The NCC experienced major magmatism and gold mineralization at ~120±10 Ma. Such spatiotemporal distribution indicates that the eastern China continent was influenced by different plate subductions, as well as ridge subductions.

Adakites formed at ~170 Ma (165.9±1.9 and 174.2±2.1 Ma) in the Daxing region, and are closely associated with porphyry Cu deposits (Figure 5). It shows slab melting has geochemical affinities with high oxygen fugacity, suggesting partial melting of subducted young oceanic crust. Daxing is located several hundred kilometers away from the Jurassic subduction zone, which is now located in the East China Sea. Therefore, the southwestward subduction of the Pacific plate commenced several million years earlier than the oldest adakite, i.e., ~175 Ma.

Further to the south, there are highly evolved granites characterized by high Li and F contents and low oxygen fugacity, many of which are classified as A-type granite. These A-type granites consist of both A1 and A2 subgroups, which are close to each other in discrimination diagrams. Tungsten-tin deposits are genetically connected to A2 subgroup granites, which are related to the dehydration of subducting slabs. These are...
Figure 3. Ages of seamounts near the bending of the Hawaiian-Emperor seamount chain and 47.5 at Daikakuji. The bathymetry and topography map was cited from Tozer et al.25

Figure 4. Drift rates of the Australian plate since the Late Cretaceous (modified after Sun et al.34) East Australia and West Australia drifted along slightly different pathways. Nevertheless, their drifting rates started to drop down quickly at ~53 Ma, reaching nearly zero at ~50 Ma, and bounced back at ~46 Ma. consistent with the southwestward subduction of the Pacific plate, e.g., oxygen fugacity decreases with increasing distance from the trench. Slab rollback first disturbed the asthenospheric mantle, resulting in mantle upwelling that forms A-type granites. During slab rollback, pressure increases rapidly, with limited increases in temperature, and thus limits subduction released fluids. Therefore, granites formed during this stage mostly plot in the field of the A1 subgroup. As slab rollback develops, the pressure increases slowly while the temperature increases rapidly. Consequently, phenigite in the cold subducting slab (~700 °C) decomposes once it is decomposed by the hot asthenosphere (~1350 °C), releasing Li and F enriched fluids. Addition of such subduction released fluids into the A-type granite source region forms highly evolved A2 subgroup granites, with very low solidus lines. Fluorine mobilizes W and Sn, forming ore deposits. Two W-Sn and fluorite metallogenic belts were successively formed in the Nanling Mountains and northeastern Jiangxi50,51,52 which are plausibly explained by two-stage slab rollback (Figure 5).50,51

Significantly, the geologic evolution of southeastern China is totally different from that of the north part of the South China Block, especially along the LYRB and the Xu-Huai region, and the North China Block. Previous studies suggested that ridge subductions occurred along the LYRB (~140 ± 10 Ma) and then the Xu-Huai region (~ 130 Ma). The LYRB is roughly linearly distributed (~30 km x 500 km), albeit with several kinks and formed within several million years (Figure 6). It consists mainly of adakite with high oxygen fugacity and show geochemical characteristics of partial melting of subducted oceanic crust. This is followed by Nb-enriched basaltic, A-type granites, and IOCG deposits.

Similar to the LYRB, the Xuhuai region also has adakite of slab melting origin and IOCG deposits, although it is much less developed compared to the LYRB. Traces of ridge subductions were also identified in the Shandong Peninsula and other places in the NCC. This is likely because the ridge was offset by several hundred kilometers due to transform faulting, and then the northward migration of the ridge after ~125 Ma. Nevertheless, all these phenomena have been plausibly explained by ridge subductions (Figure 6).27

The North China Block experienced the famous Yanshanian Events, which consist of two major compression periods separated by a period of extension (Figure 7). It also resulted in destruction of the NCC in the Early Cretaceous, with major magmatism and gold mineralization as part of the Yanshanian Movement. These are again, very different from geologic evolutions of the southeastern China and the LYRB, suggesting that the plate subduction beneath the NCC was different from that under southeastern China, in terms of age and subduction directions. The Yanshanian Movement consists of two compressions, which are named the Yanshanian Movement, Events A and B.25,48,49,50,51,156 These events are closely associated with high oxygen fugacity and IOCG deposits. A-type granites and IOCG deposits.

MAGNETIC ANOMALIES ON THE PACIFIC PLATE

Discovered in 1963, magnetic anomalies on ocean floors provide solid evidence supporting the spreading from oceanic ridges and thus the plate tectonic theory. It is widely used in plate reconstruction, especially with the development and application of software packages, e.g., GPlates. In general, magnetic anomalies are particularly reliable for the reconstruction of oceanic plates that have not yet experienced any plate subduction. Nevertheless, the whole lithosphere has been drifting on the asthenosphere ever since the beginning of plate tectonics. Therefore, plate reconstructions using magnetic anomalies need a reference frame to start with. This is
Based on the assumptions, the mainstream reconstruction model of the Pacific plate currently holds that the ridge between the Pacific and the Izu-Namibi plates was roughly parallel to the trench and subducting towards the East Asian continent\(^{18,19}\) and the Philippines plate at ~50 Ma, in a manner similar to the subduction of the ridge between the Farallon and the Pacific Plates along the eastern Pacific convergent margins. However, the differences between the trench-arc-basin system in the western Pacific convergent margins and the continental margin arc systems in the East Pacific convergent margins, as well as the different evolution of the East Asian and the North American continents, are so significant that they do not support such a model.\(^{20,21}\) More importantly, according to this plate reconstruction scheme, the time of ridge subduction, \(^{125}\) is coincident with the beginning of Cenozoic subduction in the western Pacific (~52 Ma),\(^ {21}\) which is difficult to achieve from a dynamic perspective.\(^ {21}\) Significantly, the International Ocean Discovery Program (IODP) Expedition 351 found that the Amami Sankaku Basin developed in the Izu-Bonin-Mariana convergent margin before the subduction initiation, which is consistent with sinking old oceanic crust, either through extension,\(^ {22}\) or through compression,\(^ {23}\) rather than subduction of a young spreading ridge.

The current reconstruction of the Pacific plate is based heavily on the Japanese, the Pacific and the Phoenix Lineations, assuming a stationary Pacific plate before 83.5 Ma. The Japanese Lineation represents magnetic anomalies formed during the spreading of the ridge between the Pacific and the Izu-Namibi plates. It is now roughly parallel to the current Japan trench, which was taken as the orientation of the ridge.\(^ {24}\) In contrast to the orientation indicated by the current distribution of the Japanese Lineation, as mentioned above, studies on Early Cretaceous magmatism in central eastern China show that the ridge between the Pacific and Izu-Namibi Plates was nearly perpendicular to the trench and subducted underneath the middle and lower reaches of the Yangtze River at ~150–135 Ma and then the Xu-Huai region at ~130 Ma.\(^ {25,114}\) A similar ridge orientation was obtained based on the distribution of sedimentary and igneous rocks in Japan.\(^ {21}\) Studies on the Hawaiian-Emperor seamount chain suggest that the Meiji and the Detroit seamounts erupted on the fossil ridge between the Pacific and the Izu-Namibi plates\(^ {26,27}\), which is roughly perpendicular to the Japanese Lineation. These differences are mainly due to the rotation of the Pacific plate at ~125 Ma.

**Figure 5. The distribution of magmatism and ore deposits in the southeastern China** (modified after previous studies\(^ {106,117}\)). Dextra porphyry Cu-Mo-Au deposit is located at the northeast corner of the southeastern China. There are three fluorite belts, two in the Late Jurassic and one in the Early Cretaceous, due to slab rollback and the steering of the Pacific plate.\(^ {125}\) Two Jurassic polymetallic W deposit belts are attributed to slab rollback.\(^ {106}\) The distributions of magmatism and ore deposit indicate that the Pacific plate was subducting southwestward during the Jurassic.

**ROTATION OF THE PACIFIC PLATE IN THE EARLY CRETACEOUS**

In general, neighboring magnetic anomaly lines are more or less parallel to each other, unless they have been disrupted by major tectonic events. The Pacific magnetic anomaly lines before and after the Cretaceous Superchron (125.93-83.64 Ma) are not parallel to each other (Figure 8).\(^ {130}\) Significantly, the angles between M0 and 34 are both ~25° for the Hawaiian and the Japanese Lineations. These angles were previously attributed to the rotation
of the corresponding spreading ridges, which means that the Japanese Lineation did not change its orientation ever since its formation, i.e., it represents the orientation of the spreading between the Pacific and Izanagi plates through the history. However, to form the same angles in the Japanese and the Hawaiian Lineations at the same time, the spreading ridges of the Pacific plate versus both the Izanagi and the Farallon plates should rotate by the same amount simultaneously.

The spreading of oceanic ridges is passive, such that a ridge cannot rotate by itself. The apparent rotation of a spreading ridge is usually controlled by the rotation or changing drifting rates of at least one of the two corresponding plates. Therefore, it is very difficult for the two spreading ridges of the Pacific plates to coordinate and rotate by the same amount at the same time. Instead, these two angles are plausibly explained by a counterclockwise rotation of the Pacific plate by ~50° induced by the eruption of the Ontong Java Plateau.

In principle, the angles between magnetic anomalies M0 and 34 themselves suggest that the rotation of the Pacific plate may have occurred at any time during the Cretaceous Superchron between 125.93 and 83.64 Ma. Fortunately, the age distribution of the Shatsky Rise suggests that the rotation occurred at ~125 Ma. In fact, there was only one major event on the Pacific plate that may have resulted in such major changes, i.e., the eruption of the Ontong Java plume head at ~125 Ma.

The arrival of the hot plume head lowers the density of the overriding lithosphere through thermal expansion, which may uplift the overriding plate by several hundred meters. Meanwhile, the upwelling plume head forms huge amount of basaltic magma with density ~20% lower than the surrounding mantle, which also uplifts the overriding plate. For a plume head that forms large igneous province, the total volume of the magma erupted ranges from millions to hundreds of millions of cubic kilometers, which may result in an uplift of several kilometers. For example, the eruption of the Emeishan large igneous province resulted in kilometer scale uplift.

The Ontong Java plume head formed the Ontong Java and the Manihiki Plateaus. It has erupted more than 6 million km$^3$ of basaltic magmas at the southeastern corner of the Pacific plate, which may have lifted the Pacific plate up by more than 3 km, such that it tilted the Pacific plate and consequently pushed the Pacific plate northwesternward. Meanwhile, large quantifies (~80%) of plume magmas are kept in the asthenosphere and spread at the base of the lithospheric mantle. This dramatically lowered the viscosity of the asthenosphere and promoted the drifting ability of the Pacific plate. It is noteworthy that the Pacific plate started to subduct underneath southeastern China at least in the Late Jurassic. As discussed above, the spatial and temporal distribution of igneous rocks and ore deposits suggest that it has been subducting southwestward since the Jurassic. Such that the subducting slab pulls southwestward. These two forces together resulted in the counterclockwise rotation of the Pacific plate by 50°.

Meanwhile, the drifting direction of the Pacific plate changed from south-

![Figure 6. Ridge subduction and the LYRB ore deposit belt](image-url)
west-westward (~265°) to northwestward (~300°) due to the eruption of the Ontong Java plume head. Therefore, the 80° bend in the Shatsky Rise was actually the combination of spin by 50° and changes in drifting direction. In contrast to the Japanese and the Hawaiian Lineations, the magnetic anomalies of the Phoenix Lineation were disturbed/destructed by the eruption of the Ontong Java and the Manihiki Plateaus, both of which were parts of the Ontong Java plume head erupted near the spreading ridge between the Pacific and the Phoenix plates and are now separated by the Ellice Basin (Figure 8). The spreading center of the Ellice Basin jumped to the Osbourn Trough shortly after the eruption of the plume head, as a result of the changed drifting regime.

The Pacific plate changed its drifting direction from southwestward to northwestward, due to the eruption of the Ontong Java plume head, creating spreading centers along two directions at its southeastern corner, i.e., forming the oxbow-shaped Osbourn Trough, which is kinked around the Manihiki Plateau (Figure 8). Both spreading centers were subsequently abandoned due to ridge jump. The rotation of the Pacific plate resulted in major changes in the geologic evolution of eastern China. The rotation accelerated the subduction of the north part of the Pacific plate, which had stronger interaction with the overriding plate, and thus promoted the destruction of the NCC. This is followed by fast slab rollback, which was responsible for the Cretaceous large scale magmatism and mineralization in eastern China.

ROTATION OF THE IZANAGI PLATE IN THE LATE JURASSIC

In addition to the angle between M0 and 34, there is also an angle of ~25° between M21 and M16 in the Japanese Lineation. In contrast, there is essentially no angle between the Hawaiian and the Phoenix Lineations at this time (Figure 8). M21 corresponds to 149.35-148.44 Ma, and M16 corresponds to 140.42-141.64 Ma. Previous studies also noticed this angle, which was attributed to a clockwise rotation of the spreading ridge between the Pacific and Izanagi plates by ~24° before ~147 Ma. In principle, this rotation may have occurred at any time between 149.35 Ma and 140.42 Ma. The age of this rotation is roughly coincident with the formation of adakite in the LYRB and the eruption of the Shatsky Rise (~147 Ma). As discussed above, the rotation of a spreading ridge is usually controlled by
the relative motions of the corresponding plates. There is no angle of this age in the other two magnetic lineations, indicating that it was formed by a ~50° clockwise rotation of the Izanagi plate relative to the Pacific plate, which occurred sometime between ~149 and 140 Ma.

The spatiotemporal connection seemingly suggests that ridge subduction along the LYRB was responsible for the rotation of the Izanagi plate relative to the Pacific plate, which occurred sometime between ~149 and 140 Ma.

The magnetic anomalies of the Pacific plate (modified after Sun et al.16) The Japanese Lineation shows two angles between M16 and M21, and between M0 and 34. The first angle was due to a clockwise rotation of the Izanagi plate relative to the Pacific plate between 149.35 Ma and 140.42 Ma, whereas the second angles were resulted from the counterclockwise rotation of the Pacific plate relative to the Izanagi and Farallon plates at ~125 Ma. Data from GeoMapApp and Seton et al.21

A collision may have occurred between a micro continent/island on the Izanagi plate with eastern China, which is now located in the East China Sea and the Yellow Sea.19 It was originally proposed that the collision occurred in the Cretaceous.19 Detrital zircon data suggested that the East China Sea basement merged with the East Eurasian continent at ~150 Ma.19 This is the most likely reason that caused the rotation of the Izanagi plate relative to the Pacific plate, which formed the angle in the Japanese Lineation, but not in the other two Lineations.

RECONSTRUCTION OF THE PACIFIC PLATE

We reconstructed the Pacific plate following two steps. First, pull back
Hawaiian-Emperor bend was located ~280 km to the north of the current Hawaiian Island (Figure 9A).

The Pacific plate drifted ~4400 km north-northwestward between ~52 and ~100 Ma. The bend age of 52 Ma was based on dating results of the Mussian Ridges (Figure 1). It is generally accepted that the Emperor seamount chain erupted between ~47 and ~85 Ma. The volcano at the Hawaiian-Emperor bend, Diakjuki, is dated at 46.7 ± 0.1 Ma or 47.6 Ma. However, this seamount has geochemical characteristics dramatically different from those of other Emperor seamounts. The other seamounts near the bending are Kimmeli (47.9 ± 0.2 Ma) and Yurakaku 47.4 Ma, such that ~47 Ma is well accepted as the age of the bending, which is ~4 Ma younger than the oldest forearc basalts in the Izu-Bonin-Mariana convergent margin (52 Ma). It is also ~2 Ma younger than the oldest basalt from the Amami Sankaku Basin. However, it is roughly the same age as the oldest arc volcanics rocks in the Izu-Bonin-Mariana convergent margin. Considering that both forearc basalts and Amami basalts are highly depleted without any signals of plate subduction, it may have taken the Pacific plate several million years to finish the initiation of the northwestern subduction of the Pacific plate in the Cenozoic. In addition, the Emperor chain was influenced by plume-ridge interactions, such that it cannot be used directly to reconstruct the Pacific plate. Instead, we chose the Wentworth seamount chain to pin down the position of the Pacific plate at ~100 Ma (Figure 9B).

As discussed above, the 50° counterclockwise rotation of the Pacific plate occurred at ~125 Ma, due to the eruption of the Ontong Java plateau. When this is established, the orientation of the Pacific plate changed from northeast-southwestward, which is roughly parallel to the current subduction zone, to northwest-southeastward (~290°), i.e., the ridge between the Pacific and the Izanagi plates was oriented towards ~290°, whereas the Pacific plate drifted towards ~265° and the Izanagi plate northward.

The Ontong Java plume head erupted at ~125 Ma near the Phoenix spreading ridge. The Pacific plate tilted it, resulting in major changes in the driving forces and consequently the drifting directions. After that, the Pacific plate drifted northward as illustrated by the Ojiri Rise. It shows that the Pacific plate drifted towards ~300° after the eruption of the Ontong Java plateau (Figure 9C).

It is noteworthy that the Shatsky Rise erupted near the triple junction among the Pacific, the Izu-Bonin, and the Farallon plates. It probably recorded the orientation of the ridge, rather than the drifting direction of the Pacific plate.

**PLATE SUBDUCTION AND THE YANSHANIAN MOVEMENT IN THE NCC**

The term “Yanshanian Movement” was originally coined to represent a major unconformity in an intracratonic orogen in the Yanshan Mountains. It is the most important geologic event in the Mesozoic in eastern China, consisting of episodic contractions and extensions. A variety of tectonic models have been proposed to explain the contractions, with models ranging from thin-skinned fold-thrust tectonics, out-of-sequence thrusting, the far-field compression related to the closure of the Mongol-Okhotsk Ocean to the subduction of the Pacific plate. Nevertheless, increasing evidence suggests that it is induced by Pacific plate subduction. Analogue modeling experiments suggest that the drifting of oceanic plates in the southeast pushed the southwestern margin of the NCC, and thus it was wedged into the East Asian continent, forming fold belts in weak zones surrounding the NCC (Figure 10).

The first contraction in the Yanshanian Movement, known as Event A, represented by Unconformity A, occurred at ~165-170 Ma, which is now generally attributed to the subduction of the Paleo-Pacific plate (i.e., the Izu-Bonin plate) under the NCC. The flat subduction of a composite terrane slab.

The distribution of the ridge between the Farallon and Pacific-Izanagi plates suggests that both the Pacific and the Izu-Bonin plates have westward motion components. Event A occurred later than the commencement of the southward subduction of the Pacific plate, but much earlier than the ridge subduction along the Yangtze River Belt. We suggest that the Event A of the Yanshanian Movement was induced by compression just before the initiation of the Izu-Bonin plate subduction, whereas the following
extension was due to relaxation after the subduction initiation.

As shown by magmatic and tectonic characteristics, ridge subduction along the LYRB was not symmetric. In contrast to abundant magmatism and mineralization in the southeastern China, major Late Jurassic compression to the north of the LYRB suggests that the subduction of the Izanagi plate underneath the NCC was not initiated (Figure 6). Instead, the Izanagi plate was likely still attached to the NCC when the Pacific plate was subducting southwestward. The major driving force for Event A of the Yanshanian Movement was the northwestward drifting of the Izanagi plate, which dramatically weakened once subduction initiated.

This is supported by the age distribution of Jurassic volcanic rocks, which decreases westward from 166–153 Ma in Western Liaoning to 157–142 Ma in Yuxian.204 Volcanism usually develops during the extension period. The oldest volcanic rock suggests that the subduction of the Izanagi plate started at ~166 Ma, which is coincident, within error, with the end of Event A contraction. Meanwhile, the youngest volcanic rock (~142 Ma) marginally postdates the beginning of Event B.

Event B of the Yanshanian Movement occurred at ~135–150 Ma,159,160,207 which was coincident with the peak of adakite formation in the LYRB. However, the Pacific plate was subducting southwestward at 265°. Therefore, it cannot be responsible for Event B of the Yanshanian Movement. Instead, it was likely induced by the collision between a micro-continent/island with eastern China.

Previous studies suggested that there was a micro continent in the current East China Sea and the Yellow Sea that collided with the NCC in the Early Cretaceous101 or Late Jurassic.102 Ages and isotope compositions of detrital zircon from a drill core in the East China Sea show that sediment source changed at ~150 Ma. Namely, zircon grains younger than 150 Ma show clear Cathaysia affinity, whereas those older than 150 Ma are different.105 In general, sediment provenance changes when two separated blocks become sufficiently close. However, this does not necessarily mean collision. For example, the hard collision between the Indian and the Eurasian continents started at ~53 Ma,106 or 55 Ma,208 which is several million years later than the changes in sediment provenance.209 Considering that the clockwise rotation of the Izanagi plate occurred between 149.35 Ma and 140.42 Ma, the collision likely commenced around the same time. This is very close to the beginning of Event B of the Yanshanian Movement. Once again, the NCC wedged further into the East Asian continent, forming fold belts simultaneously in three directions.15

Meanwhile, the ridge between the Pacific and the Izanagi plates started to subduct northwestward in the Xu-Huai region.2 The subduction of the young oceanic plate may have reached the gravity gradient belt and dehydrated,209 forming a big mantle wedge through slab rollback. The dehydration of serpentinites in the subducted slab formed a weak zone at depths of ~100 km in the NCC, which promoted the destruction and the formation of gold deposits.7

CONCLUSIONS

An angle of ~25° between M16 and M21 in the Japanese Lineation suggests that the Izanagi plate rotated clockwise by ~50° between 149.35 Ma and 140.42 Ma. This is likely due to the subduction of the ridge on the Pacific side underneath the LYRB. Based on angles of 25° in both the Japanese and the Hawaiian magnetic anomalies, the Pacific plate rotated anticyclonically by 50° at ~125 Ma. Therefore, the ridge between the Pacific and the Izanagi plates was oriented towards 290°. Meanwhile, its drifting direction changed from southwestward (265°) to northwestward (300°), resulting in the bend at the end of the Shatsky Rise. These were triggered by the eruption of the Ontong Java plateau. Based on these results, we propose a new reconstruction model for the Pacific plate, taking plate rotations into consideration.

The Yanshanian Movement in eastern China was mainly controlled by the drifting and subduction of the Pacific and the Izanagi plates. The Izanagi plate was likely connected to the NCC in the Late Jurassic. Its westward drift resulted in compression known as Event A of the Yanshanian Movement at 165–170 Ma. The compression was relaxed once the subduction of the Izanagi plate underneath the NCC initiated. This was followed by extension induced by slab rollback. The collision between a microcontinent in the East China Sea and the NCC commenced at ~150 Ma and was responsible for the Yanshanian Movement, Event B.

The rotation of the Pacific plate induced by the Ontong Java plume head resulted in major slab rollback at ~125 Ma, which induced large scale magmatism and the destruction of the NCC, and consequent mineralization.

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AUTHOR CONTRIBUTIONS
W.S. initiated this study and drafted the manuscript. W.S. and S.L. revised the manuscript together.

DECLARATION OF INTERESTS
The authors declare no competing interests.

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