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Abstract：

Mongol-Okhotsk Orogenic Belt is the last main orogen that constructs modern tectonic framework of northeastern Asia. It has recorded the long-term evolution of the Mongol-Okhotsk Ocean (MOO) from its Early Paleozoic initial opening, through the Late Paleozoic-Early Mesozoic subduction, to its Mesozoic final closure, leading to the amalgamation of the Siberian Craton (SIB) and North China-Amuria Block (NCC-AMB). Opening of the MOO can be traced to the early stage of the Early Paleozoic. Northward subduction of the Mongol-Okhotsk oceanic slab beneath the southern margin of the SIB initiated in the Silurian, whereas the southward subduction beneath the northern margin of the NCC-AMB started in the Late Devonian. The bidirectional subduction of the Mongol-Okhotsk oceanic slab resulted in pulse arc magmatism, with three main peaks in the earliest Carboniferous, Late Permian and Late Triassic-Early Jurassic. In the Late Triassic, the collision between the AMB and Western Mongolian Blocks led to the bending of the Western Mongolian Blocks, which caused the initial closure of the MOO in its western segment. Due to the clockwise rotation of the SIB and counterclockwise rotation of the NCC-AMB, the MOO showed a scissor-like closure from west to east. The final closure of the MOO occurred in the Middle-Late Jurassic, which also resulted in the formation of the Mongol Orocline. Since then, the

amalgamation of blocks in northeastern Asia has finished, and the northeastern Asian continent went into the intraplate evolutional stage.

Keywords: Northeastern Asia; Mongol-Okhotsk Ocean; Paleozoic-Mesozoic, Subduction initiation; Scissor-like closure

1. Introduction

Orogenic belt is the one of the best windows to study continental crustal evolution and plate tectonics, therefore, it becomes the frontier and hot realm of the Earth sphere interaction and Earth system science. According to the classical Wilson cycle, an evolution of orogenic belt starts from opening of an oceanic basin, and due to the subduction of oceanic slab, continental blocks approach each other gradually, leading to final collision and formation of orogenic belt. The Mongol-Okhotsk orogenic belt, located in northeastern Asia, recorded the subduction of the Mongol-Okhotsk Ocean (MOO), the collision between the Siberian Craton (SIB) and North China Craton (NCC)-Amuria Block (AMB), as well as the post-orogenic continental uplift (Zonenshain et al., 1990; Zorin et al., 1999; Kelty et al., 2008; Sun et al., 2013; Xu et al., 2013a; Khanchuk et al., 2015; Van der Voo et al., 2015; McDannell et al., 2018; Meng et al., 2020; Sorokin et al., 2020; Yi and Meert., 2020), and it is the last main orogenic belt that constructs the modern tectonic framework of northeastern Asia. Different from a classic collisional orogenic belt, relative rotations of the SIB and NCC-AMB resulted in a scissor-like closure of the MOO from west to east (Zonenshain et al., 1990; Xu et al., 2013a, b; Sun et al., 2013; Wang et al., 2015; Khanchuk et al., 2015; Yang et al., 2015; Gordienko et al., 2019; Sorokin et al., 2020) and the formation of the Mongol orocline (Xiao et al., 2018; Liu et al., 2021; Wang et al., 2022; Li et al., 2022). Therefore, constraining evolution of the MOO in different stages from its initial opening and subduction to final closure will be crucial to decipher the regional tectonics of northeastern Asia. However, due to its long and complex evolutional history of oceanic subduction and diachronous closure from the Paleozoic-Mesozoic, the tectonic evolution of the MOO is still hotly debated.

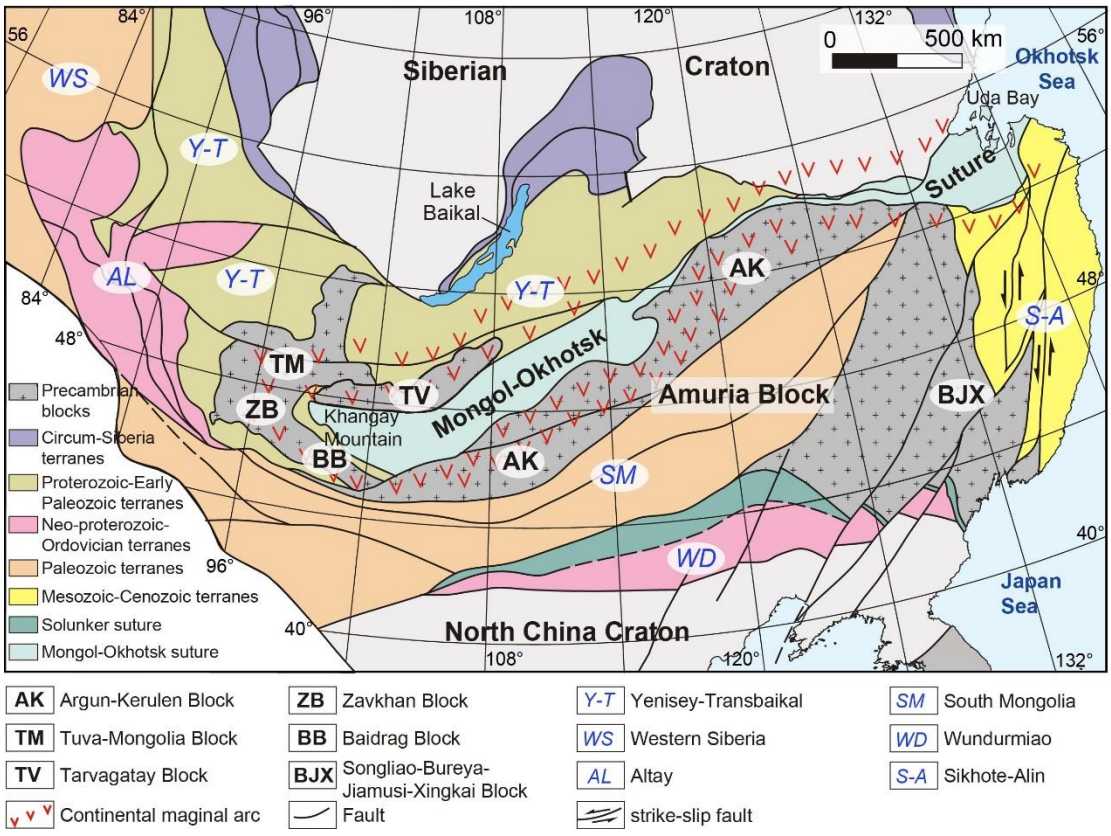

Figure 1. Tectonic framework of northeastern Asia, emphasizing on the Mongol-Okhotsk suture (modified from Parfenov et al., 2009).

The Mongol-Okhotsk orogenic belt (original named as fold belt) was firstly proposed by the Soviet geologist A.E. Fersman in 1926 (Fersman, 1926), suggesting the final suture of the MOO. It stretches over 3000 km from the Khangay Mountain in central Mongolia, via northeastern Mongolia and Heilongjiang, to the Uda bay of the Okhotsk Sea (Figure 1). Due to the lack of geological record, the origin of the MOO is not well constrained. Zonenshain et al. (1990) proposed a long-term evolution of the MOO from the Silurian to Jurassic based on geological evidence including Paleozoic-Mesozoic marine deposits (Kelty et al., 2008; Bussien et al., 2011; Ruppen et al., 2014; Yang et al., 2015) and subduction related magmatic rocks (Donskaya et al., 2012; 2013; Sun et al., 2013; Xu et al., 2013a, b; Tang et al., 2014; 2016; Sheldrick et al., 2 020) along the southern margin of the SIB and northern margin of the AMB (constituted by the Ergun-Kerulen Block, South Mongolia accretionary system, Songliao-Bureya-Jiamusi-Xingkai Block; Fig 1). For the closure of the MOO, Zonenshain et al. (1990)

also suggested a gradual closure of the MOO from west to east based on the west-east younging trend of marine deposits and continental arc magmatism along both sides of the Mongol-Okhotsk suture. This model is supported by geological evidence of multidiscipline and was named as "scissor-like closure" (Natal'in, 1993; Zorin et al., 1999; Sun et al., 2013; Wang et al., 2015; Khanchuk et al., 2015; Yang et al., 2015; Sorokin et al., 2020). However, the timing of the MOO's closure is still hotly debated.

In this paper, by integrating different aspects of geological and geophysical evidence from recent and our own studies, we discussed the initial opening, subduction and final closure of the MOO, especially the most controversial issues and possible breakthrough points. Based on the discussion, we try to constrain the evolution of the MOO and its final closure.

2. Main tectonic units of the Mongol-Okhotsk suture

The over 3000 km Mongol-Okhotsk suture extending from the Khangay Mountain to the Uda Bay shows different evolution histories from west to east, with different rock assemblages, kinematic and metamorphic features for different segments. We divided the Mongol-Okhotsk suture into four segments from west to east (Khangay Mountain, central Mongolia, northeastern Mongolia-Transbaikal and Ergun segments) and compared their rock assemblages, kinematic and metamorphic features in the following.

The Khangay Mountain segment represents the westernmost part of the Mongol-Okhotsk suture. Its basement is constituted by the Neoproterozoic-Early Cambrian Bayan-Khongor accretionary complex including ophiolite, arc volcanic rocks, pelagic and shallow marine sediments that was overlain unconformably by the Cambrian-Ordovician Dzag Formation Brachiopods-bearing flysch and carbonate (Figure 2; Gordienko et al., 2019). Age of the Bayan-Khongor ophiolite is 655-636 Ma (Buchan et al., 2001, 2002; Osozawa et al., 2008; Jian et al., 2010), which is overlain by the Cambrian-Ordovician meta-mudstone, meta-sandstone and limestone (Figure 2; Buchan et al., 2001; Badarch et al., 2002). These Neoproterozoic-Early Paleozoic geological units are unconformably overlain by the widespread Devonian-Carboniferous clastic rocks, which represent marginal marine clastic deposits (Figure 2; Zonenshain et al., 1990). Detrital zircon dating results from the Devonian-

Carboniferous strata reveal a peak age of 359-357 Ma, indicating provenance from the arc magmatic rocks due to bidirectional subduction of the Mongol-Okhotsk oceanic slab (Kelty et al., 2008; Bussien et al., 2011). The Paleozoic marine deposits were unconformably overlain by the Upper Triassic non-marine clastic rocks (Badarch et al., 2002; Zhao et al., under review) and intruded by the Late Triassic granitic rocks (Wang et al., 2022).

The central Mongolia segment is located from western Ulaanbaatar to Ondorhaan that is characterized by thick Silurian-Devonian pelagic deposits. Basalt has been identified at the bottom of the Silurian-Devonian sedimentary sequence, which may represent intra-oceanic arc volcanism (Figure 2; Kurihara et al., 2009). The late Silurian-Devonian chert-turbidite are symmetrically distributed on both sides of the suture and overlain by the Carboniferous thick clastic rocks (Minjin et al., 2006). The Silurian-Carboniferous sedimentary sequence can be divided into four formations, namely the Sergelen, Gorkhi, Altanovoo and Orgioch Formations from bottom to top (Minjin et al., 2006). The Sergelen and Gorkhi Formations are mainly composed of chert and turbidite. The Sergelen Formation is weakly metamorphosed without radiolarian or other fossils that can be used for dating, whereas the Gorkhi Formation contains abundant radiolarian that assigned its depositional age of the Late Silurian-Late Devonian (Kashiwagi et al., 2004; Kurihara et al., 2009). The Altanovoo and Orgioch Formations are over 5000m-thick with Early Carboniferous brachiopods and bryozoon (Minjin et al., 2006). Two ophiolitic mélanges have been identified from this segment in the Adaatsag and Khuhu Davaa regions, age of which has been constrained at 325-314 Ma by zircon U-Pb dating (Tomurtogoo et al., 2005; Zhu et al., 2018; 2023a). The Permian and Early Triassic sequences are also marine deposits, indicating that the MOO continued at least until to the Early Triassic in this segment (Zonenshain et al., 1990). Similar to the Khangay Mountain segment, these marine strata were unconformably overlain by the Late Triassic non-marine deposits and intruded by the Late Triassic granitoids (Figure 2).

The northeastern Mongolia-Transbaikal segment is located in the Choybalsan-Chita region, belonging to the middle part of the Mongol-Okhotsk suture. The basement

is constituted by the Early Paleozoic accretionary complex, including the Late Cambrian-Early Ordovician ophiolitic mélange, representing the early stage of the evolution of the MOO (Figure 2; Gordienko et al., 2019). The Early Paleozoic accretionary complex is overlain by the Devonian-Early Carboniferous volcanic-sedimentary sequence (Figure 2), representing the island arc magmatism related to subduction of the Mongol-Okhotsk oceanic slab, such as the Onon island arc in the Mongolia-Russia border (Zorin, 1999). Paleomagnetic results reveal that the Onon island arc was far away from both the SIB and AMB, indicating that the Onon arc should be an intra-oceanic island arc within the MOO (Kuzmin and Kravchinsky, 1996). The arc magmatism ceased before the Late Carboniferous and overlain by Late Carboniferous-Permian shallow marine deposits (Figure 2; Zorin et al., 1995). The second episode of arc magmatism of the Onon arc started from the Late Permian, represented by the Late Permian-Triassic basaltic andesite and andesite. The youngest age obtained from the Onon arc magmatic rocks is ca. 197 Ma, indicating that subduction of the Mongol-Okhotsk oceanic slab continued to the Early Jurassic in this segment (Zorin, 1999). These island arc magmatic rocks were overlain by the Early Jurassic-Early Cretaceous non-marine deposits and intra-continental volcanic rocks, suggesting that the MOO may have closed in the Early-Middle Jurassic in this segment (Figure 2; Arzhannikova et al., 2020; 2022).

The Ergun segment is located to the north of the Heilongjiang River. This segment is characterized by the Paleozoic marine sediments and Mesozoic turbidite that mainly distributed in the Oldoy and Gaga-Sagayan Basins on the north margin of the Ergun-Mamyn Block (Kravchinsky et al., 2002a). The Ergun-Mamyn Block, considered as the northeastern part of the AMB, is composed of the Late Archean-Neoproterozoic basement and Neopreterozoic metamorphosed sedimentary sequence and Cambrian deformed sediments (Tang et al., 2013; Khanchuk et al., 2015; Sorokin et al., 2016). The Ediacaran-Early Ordovician arc magmatic rocks have been identified from the Ergun-Mamyn Block, which may represent continental arc magmatism during the evolution of the Paleo-Asian Ocean (Sorokin et al., 2017). Magmatic rocks are scare within the suture zone. The Pikan magmatic complex, containing mainly meta-gabbro

and diorite, was identified from the northern margin of the Ergun Block as tectonic lens (Sorokin et al., 2007; 2020). Zircon U-Pb dating constrains the emplacement of the Pikan magmatic complex in the Middle Ordovician-Early Devonian (468-415 Ma), which was interpreted as continental marginal arc magmatic rocks that were drawn into the suture zone during the evolution of the MOO (Sorokin et al., 2007; 2020). Within the Mongol-Okhotsk suture, the Silurian-Jurassic marine sediments were well preserved (Figure 2). The Silurian strata are composed of metamorphosed sandstone, siltstone and conglomerate. The Devonian strata consist of metamorphosed sandstone, siltstone, limestone and chert with tuff interlayers. The Carboniferous sequence is composed of metamorphosed sandstone, siltstone and limestone. The Lower Permian strata consist of mudstone, greenschist and meta-sandstone with lens of chert and limestone (Figure 2; Turbin, 1994; Serezhnikov and Volkova, 2007). Ages of the Devonian-Permian strata were determined by fossils within the strata including coral, brachiopods and bryozoon. However, as these strata suffered from severe metamorphism and deformation, these fossils are not well preserved, resulting in questionable age assignment of these strata. Recent detrital zircon dating results from the Devonian Tungala, Dugda and Tangomen Formations in the Tukuringra terrane revealed the youngest peak ages of 207 Ma, 181 Ma and 189 Ma, respectively, indicating that they were Jurassic sediments (Sorokin et al., 2020). Meanwhile, the youngest peak ages for the Carboniferous Dzheskogon and Nekter Formations and lower Permian Bochagor Formation were obtained at 244 Ma, 202 Ma and 255 Ma, respectively, suggesting that they were deposited in the Triassic-Jurassic rather than the Carboniferous-Permian (Sorokin et al., 2020). Therefore, most previously considered Paleozoic strata may be deposited in the Triassic-Jurassic and the existence of Paleozoic marine strata is questionable that need further evidence. Detrital zircon dating results also indicate that marine deposits in the Ergun segment continued at least to the Early Jurassic, supporting previous consideration that there were Early Jurassic marine deposition in this region (Parfenov et al., 2001). The transition from marine to non-marine sedimentary environment, occurred in the Middle Jurassic and represented by the Middle-Late Jurassic coal-bearing continental deposits in the Amur, Zeya and Mohe

Basins, suggests the closure of the MOO and formation of the Mongol-Okhotsk orogenic belt (Figure 3; He et al., 2015; Smirnova et al., 2017; Duan et al., 2021).

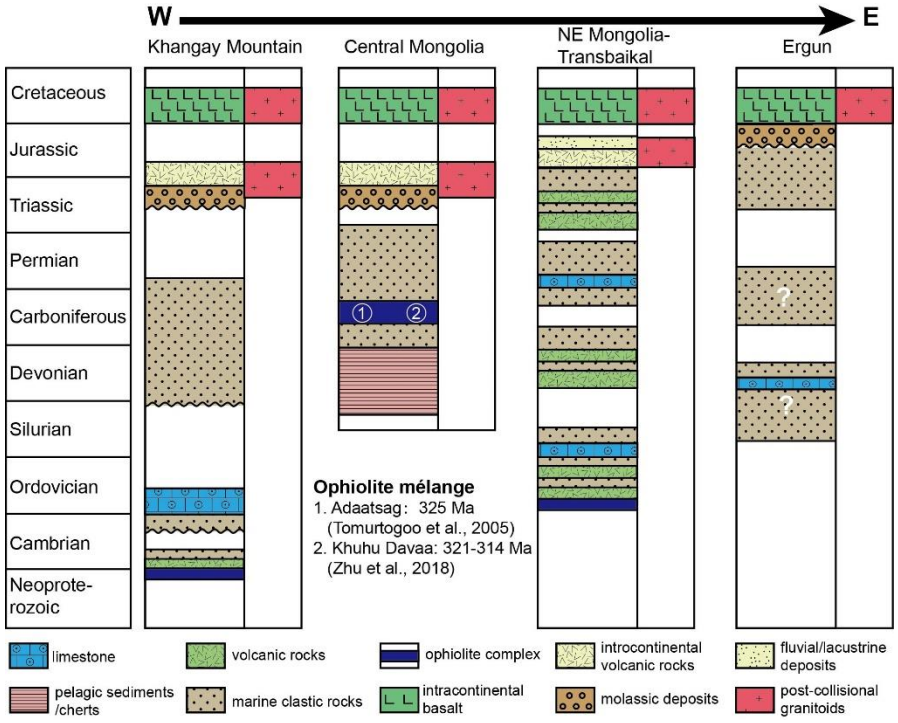

Figure 2. Strata columns of different segments of the Mongol-Okhotsk suture. (synthesized from 1:500,000 geological map of Mongolia and data from Badarch et al., 2002; Kurihara et al., 2009; Gordienko et al., 2019; Chen et al., 2022). Chronological data of ophiolitic mélange are from Tomurgogoo et al., 2005 and Zhu et al., 2018.

3. Origin and subduction of the Mongol-Okhotsk Ocean

Due to the lack of geological evidence, the origin of the MOO has not been well constrained. Nevertheless, based on the Ordovician-Silurian slices of oceanic slab identified in central and northern Mongolia, the opening of the MOO has been connected with the evolution of the Paleo-Asian Ocean (Figure 3a; Zonenshain et al., 1990; Cocks and Torsvik, 2007; Ruppen et al., 2014). Gordienko et al. (2019) proposed a rift-extension model that the MOO originated from extension of the Orkhon-Kharagol basin between the Central Mongolian and Muya-Stanovoi Blocks (Figure 3b). Another model suggests that subduction of the Paleo-Asian oceanic slab beneath the SIB in the Early Paleozoic caused back-arc extension that evolved into the MOO (Figure 3c; Badarch et al., 2002; Bussien et al., 2011; Cocks and Torsvik, 2007). Both two models

resulted in the rifting and drifting of the Central Mongolian Block (constituting the AMB since the Late Paleozoic) from the SIB with the opening of the MOO (Figure 3a; Torsvik and Cocks, 2016). The similar rifting and drifting processes also occurred for the Western Mongolian Blocks (constituted by the Tuva-Mongolia, Zavkhan, Baydrag and Tarvagatay Blocks). The Western Mongolian Blocks accreted to the margin of the SIB during the Neoproterozoic-Ordovician (Badarch et al., 2002). After short-term coevolution, the Western Mongolian Blocks rifted from the SIB in the Silurian and drifted southward, revealed by paleomagnetic results (Bold et al., 2016; Kilian et al., 2016). However, as no Early Paleozoic paleomagnetic result has ever been reported from the AMB, it is still debatable whether the AMB was rifted from the SIB in the Early Paleozoic or the oceanic basin between the SIB and AMB existed before the Early Paleozoic that was named as the MOO since the Early Paleozoic. For example, both Zorin (1999) and Li (2006) considered that the MOO was a gigantic bay of the Paleo-Pacific Ocean between the SIB and AMB.

The subduction of the Mongol-Okhotsk oceanic slab initiated in the Silurian. Calc-alkaline granotoids and accretionary complex identified along the southern margin of the SIB are the direct evidence for subduction of the Mongol-Okhotsk oceanic subduction (Zorin, 1999; Donskaya et al., 2013; Ruppen et al., 2014). Meanwhile, detrital zircon dating results obtained from the Devonian-Carboniferous strata to the north of the suture display Silurian-Devonian age peaks (Ruppen et al., 2014), indicating arc magmatism related to the subduction of the Mongol-Okhotsk oceanic slab beneath the southern margin (recent coordinates) of the SIB. The widely distributed Devonian-Carboniferous turbidites in the western and central parts of the Mongol-Okhotsk suture represent trench sediments along Andean-type continental margin (Zorin, 1999). The Silurian-Devonian magmatic rocks have also been identified from the southern side of the suture, but it is still controversial whether they can represent subduction-related magmatism or not. For example, the Late Silurian bimodal volcanic rocks identified on the Ereendavaa Block (northeastern part of the AMB) was interpreted as post-collisional magmatism following collision between the Ereendavaa Block and the Idermeg Block (Narantsetseg et al., 2019). The Late Devonian A-type

granite reported from the Ergun Block resulted from the northwestward subduction of the Heihe-Nenjiang oceanic slab beneath the Ergun Block (Li et al., 2017a). Meanwhile, detrital zircon dating results show that different peak ages from the Silurian-Middle

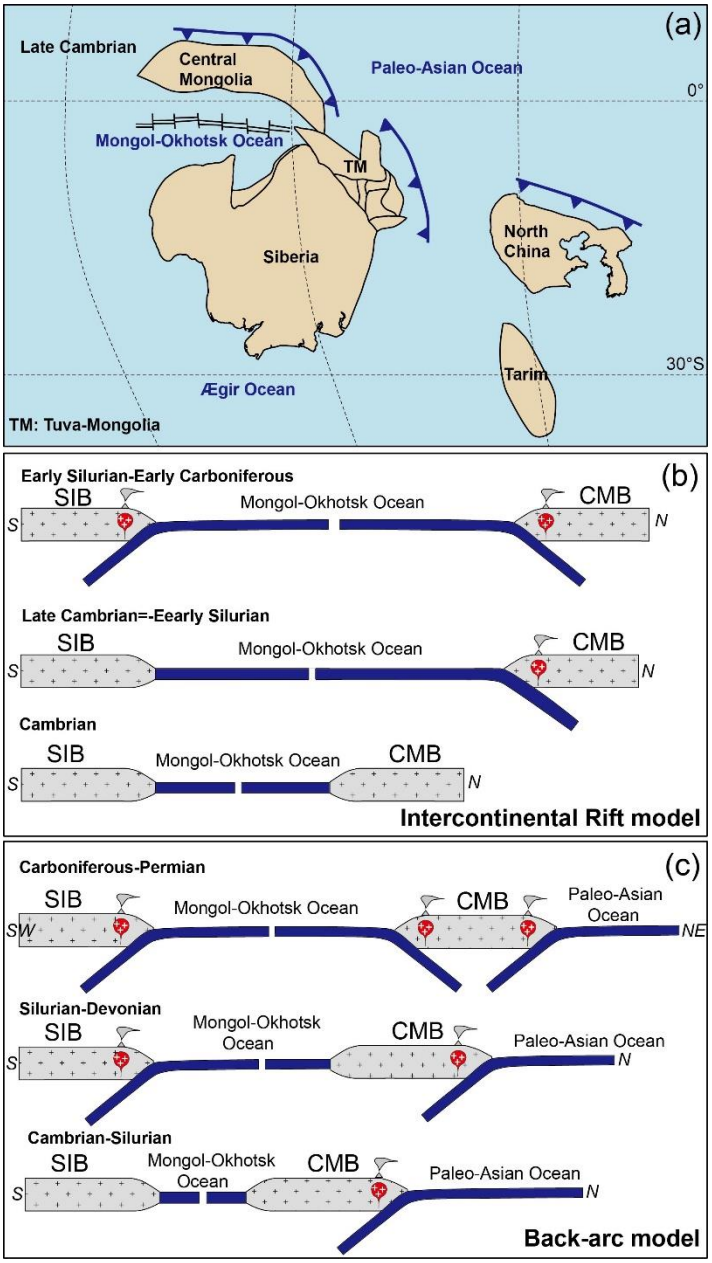

Figure 3. Models of opening of the Mongol-Okhotsk Ocean. (a) Paleogeography map of the Siberian Craton and surrounding cratons in the Late Cambrian (modified from Torsvik and Cock, 2016); (b) Intercontinental rift model (modified from Gordienko et al., 2019); (c) Back-arc extension model (modified from Bussien et al., 2011). SIB: Siberian Craton; CMB: Central Mongolian Block.

Devonian obtained from the northern side of the suture (Ruppen et al., 2014). However, strata in the southern side of the suture display no Silurian-Middle Devonian age peak (Bussien et al., 2011). The different detrital zircon age distribution patterns may consequently suggest that there was no southward subduction of the Mongol-Okhotsk oceanic slab beneath the northern margin of the AMB during the Silurian-Middle Devonian. Detrital zircon dating results obtained from the Carboniferous strata in the western segment of the suture reveal a significant age peak at about 351 Ma and some Late Devonian zircon ages (Kelty et al., 2008), indicating that the southward subduction of the MOO may have started in the Late Devonian and reached its climax in the Early Carboniferous. Recent studies show that subduction of the MOO may have started since the Cambrian-Ordovician. A new Cambrian-Ordovician Ikh-Mongol magmatic belt has recently been identified around the Mongol-Okhotsk suture with coeval subduction-related high-pressure eclogite (Figure 4a; Janoušek et al., 2018; Zhu et al., 2023b). But how this magmatic belt was formed is not clear. Although it was considered as the result of the subduction of the Paleo-Asian Ocean beneath the Tuva-Mongolia Block (Janoušek et al., 2018), due to their distribution along the Mongol-Okhotsk suture, they may also represent the Cambrian-Ordovician subduction of the MOO. More studies are need to decipher the tectonic origin of this magmatic belt. Meanwhile, two Ordovician high-K granites have recently been identified with zircon U-Pb age of 469 ± 3 Ma and 440 ± 3 Ma (Ling et al., 2021). Both granitic bodies show A_2-type geochemical characteristics, which was interpreted as the result from slab roll-back during the subduction of the MOO in the Middle Ordovician (Ling et al., 2021). Based on the study of the Late Carboniferous Adaatsag ophiolite, Zhu et al. (2023a) found that it has similar rock assemblage with the Izu-Bonin-Mariana forearc magmatic rocks, therefore, they proposed that the southward subduction of the MOO may initiated from the Late Carboniferous. However, this subduction initiation timing is not consistent with the Early Carboniferous age peak of magmatic rocks along the suture (Kelty et al., 2008).

The bidirectional subduction of the Mongol-Okhotsk oceanic slab resulted in abundant arc magmatic rocks along both continental margins of the SIB and AMB (Figure 4b; Donskaya et al., 2013; Zhao et al., 2017; Wang et al., 2022). To the north of

the suture, arc magmatic rocks contain mainly of granite, granodiorite, monzogranite, syenite and mafic rocks, showing typical continental margin arc magmatic geochemical affinity (Donskaya et al., 2013). To the south of the suture, arc magmatic rocks are mainly composed of I-type calc-alkaline to high-K calc-alkaline granite, monzogranite and syenogranite (Zhao et al., 2017; Li et al., 2018; Sorokin et al., 2021). Detrital zircon dating results obtained from Carboniferous strata within and along both sides of the suture show a prominent Early Carboniferous age peak, supporting the widely distributed subduction-related Early Carboniferous arc magmatism (Figure 5; Kelty et al., 2008; Bussien et al., 2011). Meanwhile, detrital zircon dating results reveal three age peaks of Early Carboniferous (351-344 Ma), Late Permian (257-254 Ma) and Late Triassic-Early Jurassic (207-192 Ma) for the arc magmatism related to the Mongol-Okhotsk oceanic subduction (Figure 5; Kelty et al., 2008; Sorokin et al., 2020; Chen et al., 2022), indicating pulse magmatic events that may be related to changes of angle and velocity of the subducted slab. By compilation of magmatic rocks along both sides of the suture, Wang et al. (2022) found that ages of magmatic rocks show outside to inside younging and west to east younging trends (Figure 4b-d). The Carboniferous-Early Triassic magmatic rocks have been identified around the whole suture (Tang et al., 2014; 2016; Zeng et al., 2014; Ji et al., 2018; Fu et al., 2021; Sorokin et al., 2021; Wang et al., 2022; Ovchinnikov et al., 2023), whereas the Jurassic magmatic rocks are only distributed in the central and eastern segments of the suture (Figure 4c,d; Xu et al., 2013a; Sun et al., 2013; Wang et al., 2015; Sheldrick et al., 2020), indicating that the subduction in the western segment may have ceased at the Late Triassic.

Magmatic rocks along the southern margin of the SIB and northern margin of the AMB reveal a bidirectional subduction of the MOO. However, seismic topography results only show high velocity anomaly beneath the SIB, without high velocity anomaly beneath the AMB (Van der Voo et al., 1999; van der Meer et al., 2018), arguing for a solo northward rather than bidirectional subduction of the MOO (Van der Voo et al., 1999). However, the geodynamic modeling shows that due to eastward movement and rotation of the Eurasia continent, if there was southward subduction, the subducted oceanic slab could be preserved beneath the SIB (Fritzell et al., 2016). Therefore, the

absence of high velocity anomaly beneath the AMB cannot be considered as the evidence arguing against the southward subduction of the MOO beneath the AMB.

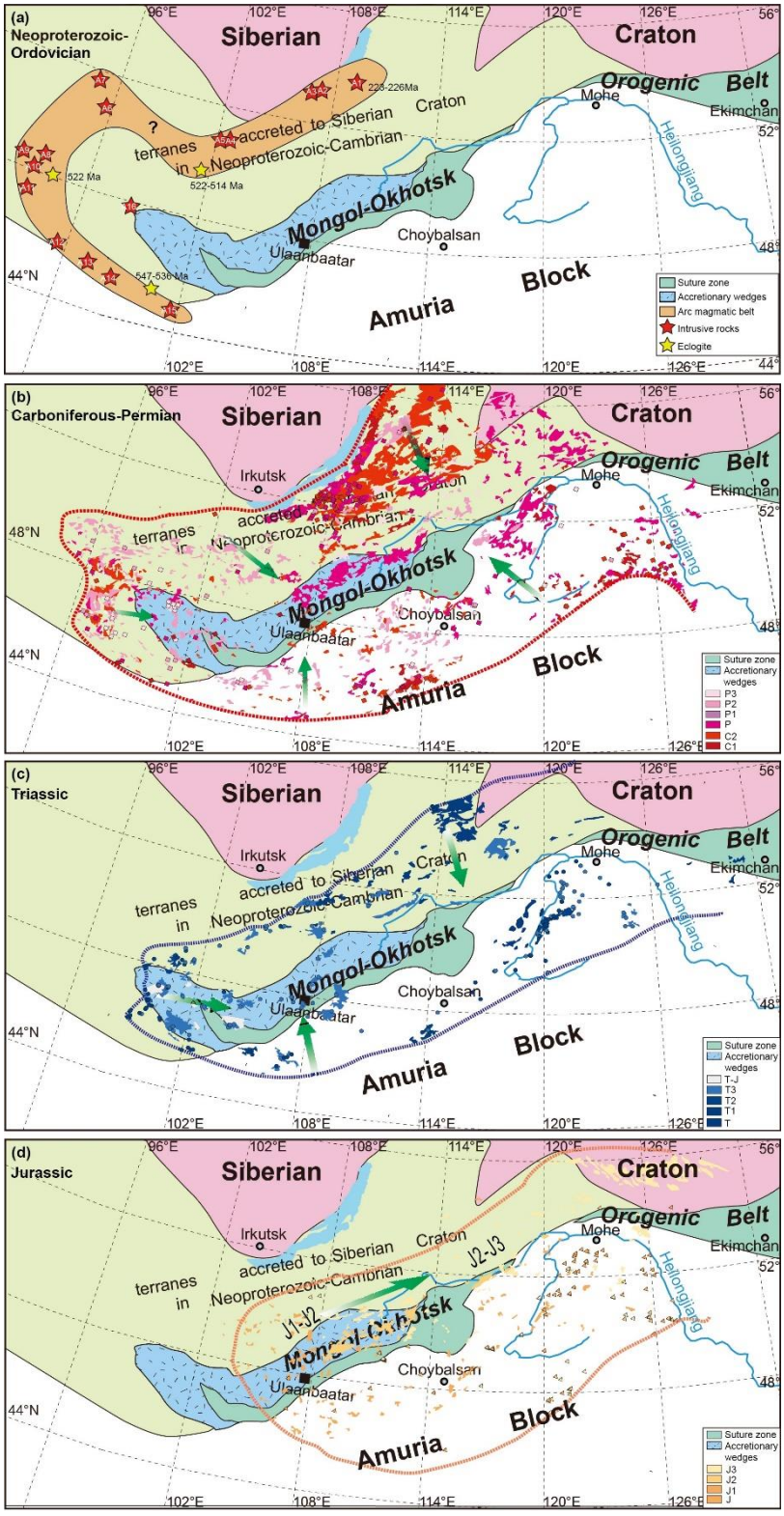

Figure 4. Distribution of magmatic rocks in different ages around the Mongol-Okhotsk suture. (a) Ediacara-Ordovician (modified from Zhu et al., 2023b); (b) Carboniferous-

Permian (modified from Wang et al., 2022); (c) Triassic (modified from Wang et al., 2022); (d) Jurassic (modified from Wang et al., 2022).

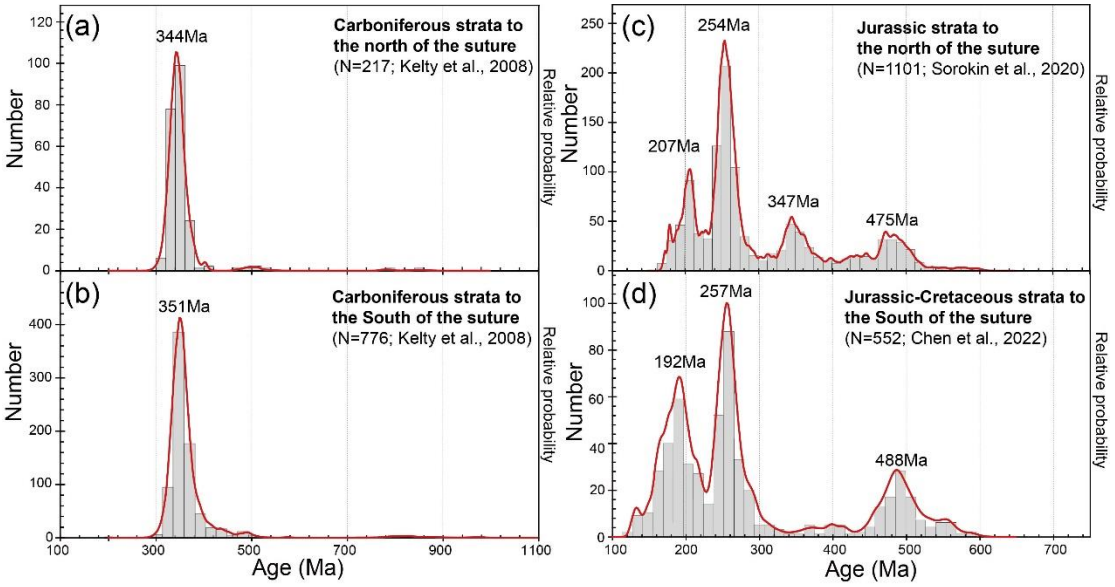

Figure 5. Detrital zircon distribution patterns of Carboniferous (a, b) and Jurassic-Cretaceous (c, d) strata from both sides of the Mongol-Okhotsk suture, showing similar Earliest Carboniferous, Late Permian and Late Triassic-Early Jurassic age peaks from both sides of the Mongol-Okhotsk suture. Detrital zircon U-Pb age data are from Kelty et al., 2008; Sorokin et al., 2020 and Chen et al., 2022.

4. Closure of the Mongol-Okhotsk Ocean

The style and timing of closure are the most controversial problems for the evolution of the MOO. Geological evidence argues for a west to east scissor-like closure of the MOO (Zonenshain et al., 1990; Zorin, 1999; Xu et al., 2013a; Gordienko et al., 2019; Sorokin et al., 2020; Arzhannikova et al., 2020; Wang et al., 2022). For example, both transition timing from marine to non-marine sediments and ages of magmatic rocks show an eastward younging trend along the suture (Zonenshain et al., 1990; Wang et al., 2022). The scissor-like closure is also supported by paleomagnetic result. By compilation of paleomagnetic data from blocks in eastern Asia, Zhao et al. (1996) proposed that the western segment of the MOO was closed in the Late Permian-Triassic, whereas the eastern segment was closed in the Late Jurassic-Early Cretaceous. On the contrary, both Enkin et al. (1992) and Van der Voo et al. (2015) considered that the

MOO was simultaneously closed in the Late Jurassic-Early Cretaceous. During the Triassic-Jurassic, the SIB experienced ~45° clockwise rotation and moved southward, and the NCC-AMB rotated ~90° counterclockwise and moved northward (Van der Voo et al., 2015). In this model, the relative rotations of the SIB and NCC-AMB caused narrowing of the MOO in a scissor-like way, resulting in the similar width of the MOO from west to east in the Late Jurassic and closure of the MOO in the Late Jurassic-Early Cretaceous. Recent sedimentological and detrital zircon dating studies on the western Baikal region (central segment of the MOO) and the Dzhagda region (eastern segment of the MOO) argue for that the central and eastern segments of the MOO should have been closed in the Early-Middle Jurassic boundary (Arzhannikova et al., 2020; Sorokin et al., 2020). However, remnant-oceanic basin still existed in the eastern Baikal region that was closed in the Middle to Late Jurassic boundary, based on which Arzhannikova et al. (2022) proposed that the closure of the MOO may not be in the scissor-like way and each segment of the MOO evolved independently. The main reason for this controversy is that the timings for the initial and final closure of the MOO are not well constrained.

4.1 Timing of initial closure of the MOO in its western segment

Zonenshain et al. (1990) proposed that the initial closure of the MOO in its western segment occurred in the Late Triassic-Early Jurassic based on the transition age from marine to non-marine deposits and ages of magmatic rocks along the Mongol-Okhotsk suture. This viewpoint is supported by the regional unconformity identified between the Upper Triassic clastic deposits and underlying geological units (Badarch et al., 2002). Meanwhile, the Late Triassic alkaline magmatic rocks were identified from the western segment of the Mongol-Okhotsk suture, emplaced in an extensional setting, arguing for a Late Triassic closure of the MOO in its western segments (Donskaya et al., 2013). Furthermore, the Late Triassic granites intruded into the Mongol-Okhotsk suture as stitching plutons and the Jurassic arc magmatism did not exist anymore along the western segment of the Mongol-Okhotsk suture (Figure 6; Wang et al., 2022). Based on these evidence, a Late Triassic closure of the MOO in its western segment was proposed, followed by scissor-like closure of the MOO (Wang et al., 2022).

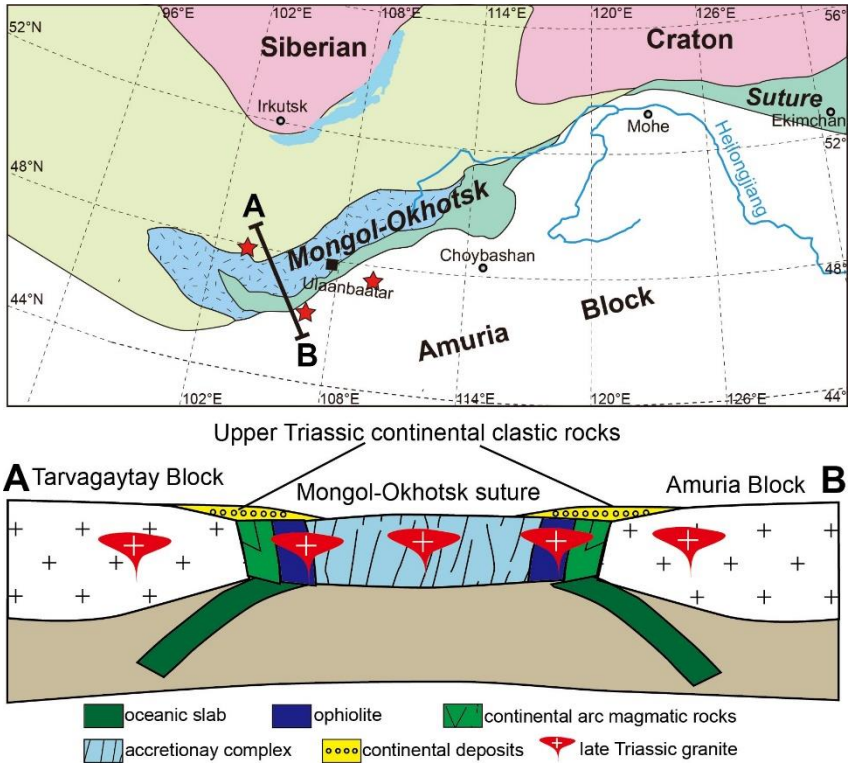

Figure 6. Cross-section across-cut the western segment of the Mongol-Okhotsk suture with location marking in the upper map. Late Triassic granites intruded into the suture zone and Tarvagatay Block and Amuria Block on both sides of the suture. The suture zone is unconformbly overlain by the Upper Triassic continental clastic rocks. Magmatic and sedimentary evidence indicates that the western segment of the MOO should have been closed in the Late Triassic. Red stars represent locations of the measured Upper Triassic strata and paleomagnetic sampling.

Concerning the initial closure of the MOO, different models have been proposed by paleomagnetic studies. By compilation of paleomagnetic data from the SIB and NCC, Zhao et al. (1996) considered that the western segment of the MOO should have been closed during the Permian-Triassic. On the contrary, Van der Voo et al. (2015) proposed a Late Jurassic-Early Cretaceous simultaneous closure of the whole MOO from west to east. The southern margin of the SIB aligned in the N-S direction in the Permian and the Western Mongolian Blocks along the southwestern margin of the SIB (Figure 1) should collide with the AMB firstly during the clockwise rotation of the SIB that led to initial closure of the MOO. New paleomagnetic data obtained in the last decade show

that the Western Mongolian Blocks accreted to the southwestern margin of the SIB during the Neoproterozoic-Cambrian (Bold et al., 2016). After a short-time coevolution, the Western Mongolian Blocks rifted from the SIB in the Silurian and drifted southward to a middle- to low-latitude since then (Bold et al., 2016; Kilian et al., 2016) until at least to the Carboniferous (Ren et al., 2021). Due to the lack of Permian-Middle Triassic paleomagnetic result for the Western Mongolian Blocks, relative positions of the Western Mongolian Blocks and the SIB during this period cannot be confined. However, considering that the SIB was located at high latitude during the Permian-Middle Triassic (e.g., the paleolatitude of the northern SIB was ~70-60° N during the Permian-Late Triassic; Walderhaug et al., 2005; Torsvik et al., 2012), the initial closure of the MOO in its western segment should be caused by the collision between the Western Mongolian Blocks and the AMB. Pruner (1992) firstly reported a Triassic paleolatitude of 32.8 ± 16.8° N from the Tarvagatay Block (a part of the Western Mongolian Blocks) to the north of the Mongol-Okhotsk suture. Although this paleolatitude yielded a big uncertainty, it is consistent with coeval paleolatitude of the NCC-AMB (Wu et al., 1990; Yang et al., 1991; Ma et al., 1993).

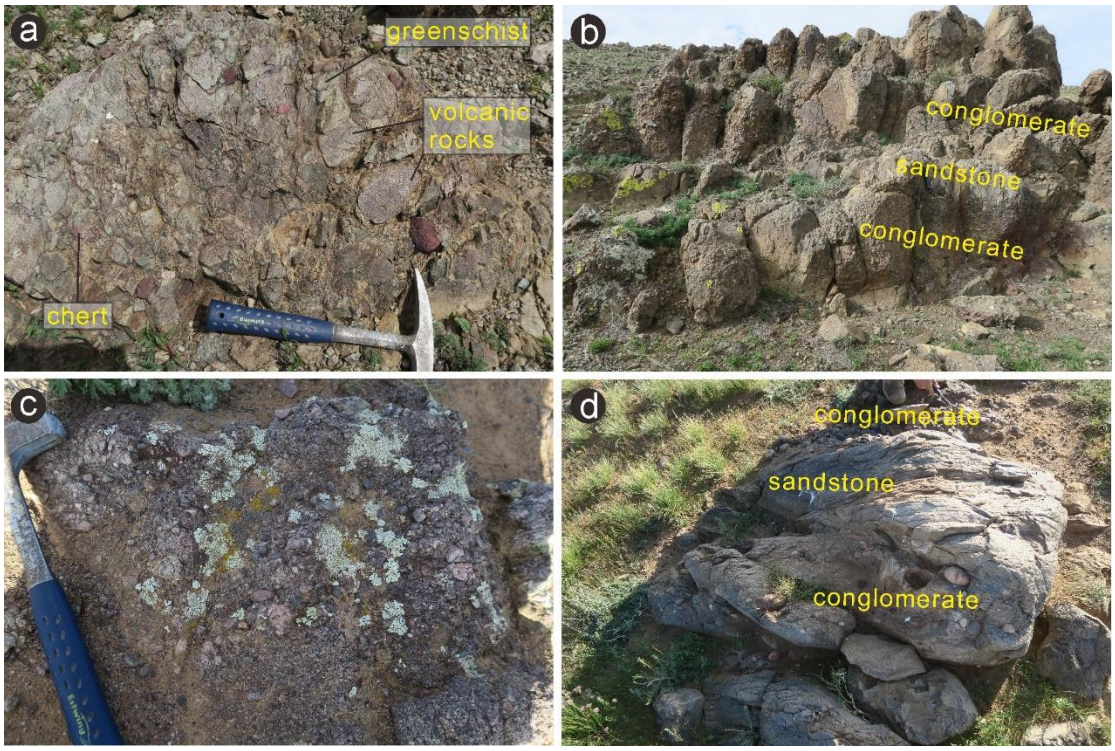

Figure 7. Photos of field outcrops of the Upper Triassic continental clastic rocks from the western segment of the Mongol-Okhotsk suture. Basal conglomerate (a) and

interbedded conglomerate and sandstone (b) from northern side of the suture, with pebbles and cobbles of volcanic rocks, greenschist, chert, etc. Basal conglomerate (c) and interbedded conglomerate and sandstone (d) from the southern side of the suture.

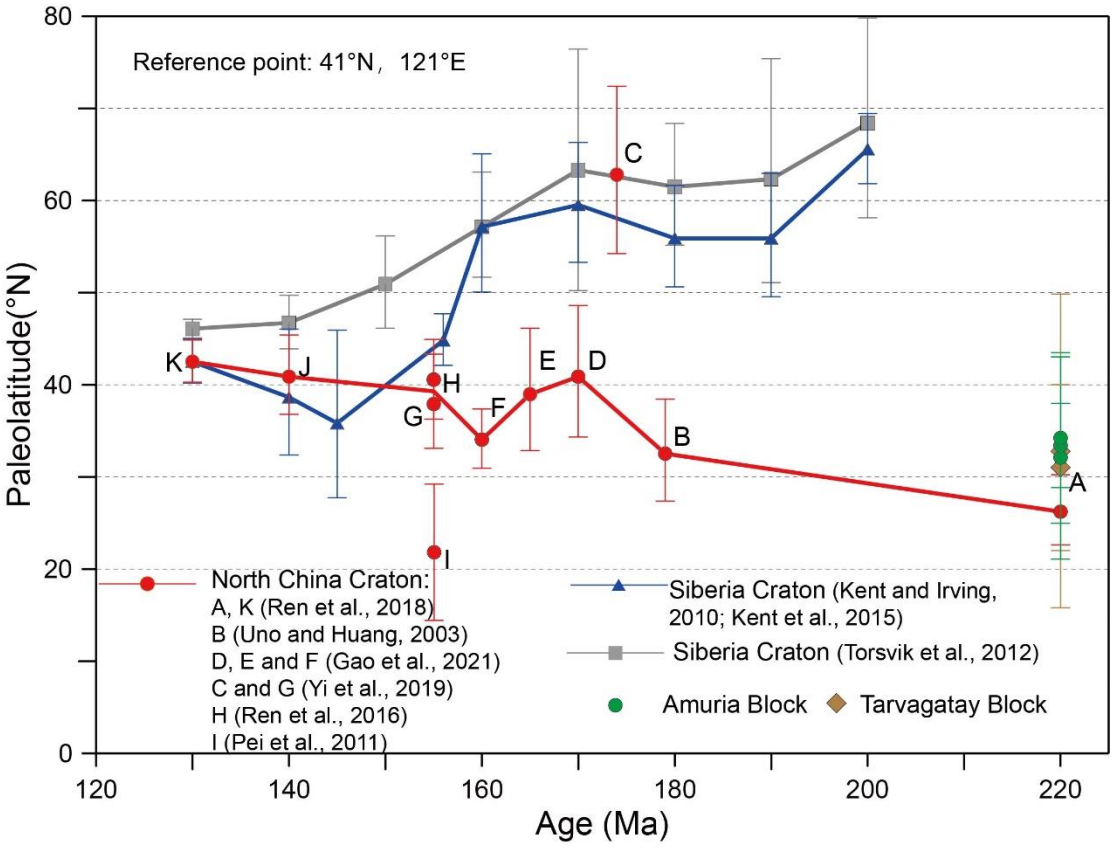

Figure 8. Paleolatitude versus time plot with the Late Triassic-Early Cretaceous paleomagnetic data of the NCC, SIB, AMB and the Tarvagatay Block. Paleolatitude data of the NCC are from Uno and Huang, 2003; Pei et al., 2011; Ren et al., 2016; 2018 and Gao et al., 2021. Paleolatitude data of the SIB are from Kent and Irving, 2010 and Kent et al., 2015. Paleolatitude data of the NCC and SIB are calculated with reference point of 41°N, 121°E. Paleolatitude data of the AMB and the Tarvagatay Block are from Pruner, 1992; Zhao et al., 2023 and Zhao et al., under review. Paleolatitude data of the AMB and the Tarvagatay Block are calculated with individual sampling location.

To test this latitudinal consistency, we performed sedimentological and paleomagnetic studies on the Upper Triassic strata from both sides of the western

segment of the Mongol-Okhotsk suture zone. The Upper Triassic strata from both sides of the suture show similar terrestrial deposits (Figure 6), with thick-bedded conglomerate at the bottom containing pebbles and cobbles of chert, greenschist, volcanic rocks etc. (Figure 7a, c), interbedded conglomerate-sandstone in the middle (Figure 7b, d), and thick-bedded sandstone in the upper part. The rock assemblages, combining with abundant plant fossils discovered from sandstone layers, indicate that the Late Triassic sedimentary sequence represents foreland basin deposits after the closure of the western segment of the MOO (Figure 6; Zhao et al., under review). Our paleomagnetic studies on the Upper Triassic strata show paleolatitudes of 31.1° ± 9.0°N for the Tarvagatay Block, 32.1° ± 10.6°N~34.2° ± 9.2°N for the northern margin of the AMB, and 33.3°± 4.6°N for the southern margin of the AMB (Figure 8; Zhao et al., 2023). The consistent paleolatitudes for the Tarvgatay Block and the AMB indicate that the MOO may have been closed in the Late Triassic.

By integrating sedimentological, magmatic, paleontological and paleomagnetic evidence, we propose that the Western Mongolian Blocks have collided with the NCC-AMB in the Late Triassic, and the initial closure of the western segment of the MOO occurred in the Late Triassic (Figure 9b).

4.2 Timing of final closure of the MOO in its eastern segment

Multi-disciplinary studies have been performed on the final closure of the MOO in its eastern segment. However, due to different methodologies and materials in focus, timing of final closure of the MOO is still hotly debated, with three main viewpoints at the Early-Middle Jurassic (Zorin, 1999; Sorokin et al., 2020; Yi and Meert, 2019), latest Middle Jurassic (Zonenshain et al.,1990; Zhang, 2011; Li et al., 2015; Sun et al., 2013; Xu et al., 2013a; Wang et al., 2015; Li et al., 2018), and Late Jurassic-Early Cretaceous (Kravchinsky et al., 2002a, b; Cogné et al., 2005; Pei et al., 2011; Van der Voo et al., 2015; Yang et al., 2015; Ren et al., 2018).

Based on detailed structural kinematic and magmatic studies, Russian geologists proposed that the SIB and NCC-AMB should have collided in the Early-Middle Jurassic (Zorin, 1999). Recent detrital zircon geochronological studies on the meta-sediments from terranes to the north of the Heilongjiang River revealed that their

456 provenance contains materials in the northern AMB (Sorokin et al., 2020). Meanwhile,
457 the absence of detrital zircon younger than 171 Ma implies that the final closure of the
458 MOO could have taken place at the boundary of the Early and Middle Jurassic as a
459 result of the collision between the SIB and NCC-AMB (Zaika et al., 2018; Sorokin et
460 al., 2020). Recent paleomagnetic study on the Lower-Middle Jurassic Nandaling
461 Formation (~174 Ma) in the northern margin of NCC shows a paleolatitude of 61.7° ±
462 9.1°N for the NCC, which is consistent with that of the SIB (Figure 8), therefore
463 suggests that the MOO should have been closed at the Early and Middle Jurassic
464 boundary (Yi and Meert, 2020).
465 According to the eastward younging trend of sedimentary and magmatic rocks on
466 both sides of the Mongol-Okhotsk suture, Zonenshain et al. (1990) proposed that the
467 main part of the MOO should have been closed in the Middle Jurassic, with only ~300
468 km width residual oceanic basin left in the easternmost segment. A same conclusion has
469 also been reached based on the ages of kinematic deformation and magmatic rocks
470 (Natal'in, 1993). Kinematic studies on the Jurassic strata in the Heilongjiang Basin
471 revealed a Late Jurassic top-to-the-south thrust, caused by regional compression related
472 to the collision between the SIB and NCC-AMB, suggesting a Middle Jurassic closure
473 of the MOO (Zhang, 2011). Magmatic rocks in the Ergun and Xing'an Blocks show a
474 transition from Late Triassic-Early Jurassic calc-alkaline magmatism to Late Jurassic-
475 Early Cretaceous A-type magmatism with a Middle Jurassic magmatic lull, suggesting
476 that the closure of the MOO should occur in the Middle Jurassic (Sun et al., 2013).
477 Meanwhile, Li et al. (2015) identified a Middle Jurassic (~168 Ma) muscovite granite
478 in NE China, the primary magma of which was derived from partial melting of a
479 juvenile thickened lower crust resulted from closure of the MOO, therefore indicating
480 a Middle Jurassic closure of the MOO. Moreover, the Late Jurassic-Early Cretaceous
481 magmatic rocks emplaced in extensional tectonic setting are widespread distributed in
482 NE Mongolia and western Great Xing'an Range of NE China (Sun et al., 2013; Li et
483 al., 2018; Tang et al., 2018). However, whether these magmatic rocks emplaced in a
484 post-orogenic extension after the closure of the MOO or back-arc extension related to
485 the subduction of the Paleo-Pacific oceanic slab is still controversial. The key to solve

this controversy is constraining regions of influence of both two tectonic regimes. Li et al. (2017b) identified Middle-Late Triassic high-Mg adakitic andesites along the southern margin of the Xing'an Block, and concluded that the Mongol–Okhotsk tectonic regime extended at least as far as the eastern margin of the Xing'an Block. Meanwhile, the Late Jurassic and early Early Cretaceous magmatic rocks are mainly distributed in the Great Xing'an Range and to its west showing a southward migration, while coeval magmatism is scare in the Lesser Xing'an–Zhangguangcai Ranges and eastern Heilongjiang–Jilin Provinces (Xu et al., 2013a). Therefore, these Late Jurassic and early Early Cretaceous magmatic rocks should be formed in a post-collisional tectonic setting after the closure of the MOO in the Middle Jurassic, rather than induced by the Paleo-Pacific subduction (Sun et al., 2013; Xu et al., 2013a; Tang et al., 2015; Wang et al., 2015; Li et al., 2018; Tang et al., 2018).

Although paleomagnetic results from the NCC-AMB are inconsistent, most available data indicate the existence of a wide oceanic basin between the SIB and the NCC-AMB. For example, Late Jurassic paleomagnetic data obtained from northern margin of the AMB and southern margin of the SIB show a 1700-2700 km distance between the SIB and AMB (Kravchinsky et al., 2002a, b; Cogné et al., 2005). Two ca. 155 Ma paleomagnetic poles were reported from the northeastern Inner Mongolia and southern Mongolia of the AMB, indicating a paleolatitudinal difference of 10°-15° for the SIB and AMB (Zhao et al., 1990; Ren et al., 2018). However, paleomagnetic studies on the Late Jurassic Tiaojishan volcanic rocks display different results. Pei et al. (2011) reported a paleomagnetic pole for the Tiaojishan volcanic rocks at 59.9°N/240.3°E, with A_{95}=6.8°, constraining a ~3000 km width of the MOO at ca. 155 Ma (Figure 8). On the contrary, a new paleomagnetic study on the Tiaojishan volcanic rocks yielded a paleomagnetic pole at 69.6°N/203.0°E (A_{95}=5.6°), indicating a ~1600 km width of the MOO at ca. 155 Ma (Figure 8; Ren et al., 2016). The Early Cretaceous paleomagnetic data obtained from southern SIB (Cogné et al., 2005; Metelkin et al., 2010) and AMB (Pruner, 1987; Halim et al., 1998; Hankard et al., 2005; Ren et al., 2018) show consistent paleomagnetic pole and paleolatitude, indicating that the MOO should have been closed in the Early Cretaceous. Meanwhile, the apparent polar wander paths

(APWPs) of both the NCC and the SIB are overlapped in the Early Cretaceous, also supporting that final closure of the MOO in the early stage of the Early Cretaceous (Van der Voo et al., 2015). This viewpoint is supported by sedimentary and magmatic evidence. Yang et al. (2015) identified a Late Jurassic-Early Cretaceous transition from marine to non-marine deposits in the eastern segment of the MOO. Meanwhile, the Late Jurassic magmatic rocks in the eastern segment show arc magmatic geochemical affinities, indicating that subduction of the Mongol-Okhotsk oceanic slab was still ongoing in the Late Jurassic and the final closure of the MOO occurred in the Latest Jurassic to Earlies Cretaceous (Ouyang et al., 2015; Wan et al., 2019).

In conclusion, geological evidence mainly supports a Middle-Late Jurassic closure of the MOO (Figure 9). The inconsistency from different aspects of geological evidence is mainly caused by the range of constraint on the timing of collision. For example, transition from marine to non-marine deposits can constrain the final disappear of the oceanic basin, however, this age can be much younger than the timing of collision as after continental collision, marine sedimentary basin can still last for long time. For example, after the collision between the Arabian Block and Eurasian continent in the Oligocene, marine deposits preserved until to present day in the Persian Gulf. Therefore, marine to non-marine transition can only provide a loose constraint on the final closure of the MOO. S-type granite represents syn-collision partial melting of thickened lower crust, age of which may be closer to the timing of continental collision. Li et al. (2015) identified a ca. 168 Ma S-type granite in the northern Great Xing'an Range, suggesting a Middle Jurassic closure of the MOO (Li et al., 2018). Detrital zircon exchange can constrain the upper limit of oceanic closure. Sorokin et al. (2020) found that the Upper Jurassic from both sides of the suture display similar detrital zircon distribution pattern, indicating that detrital zircon exchange has occurred in the Late Jurassic, therefore, the most likely timing for closure of the MOO should be the Middle Jurassic (Figure 9c). However, paleomagnetic evidence mainly argues for a Late Jurassic-Early Cretaceous closure of the MOO, younger than that concluded from geological evidence. This inconsistency from geological and paleomagnetic aspects should be noticed, and integrated geological and paleomagnetic studies should be performed in the future in

order to reach a consistent constraint on the timing of closure of the MOO.

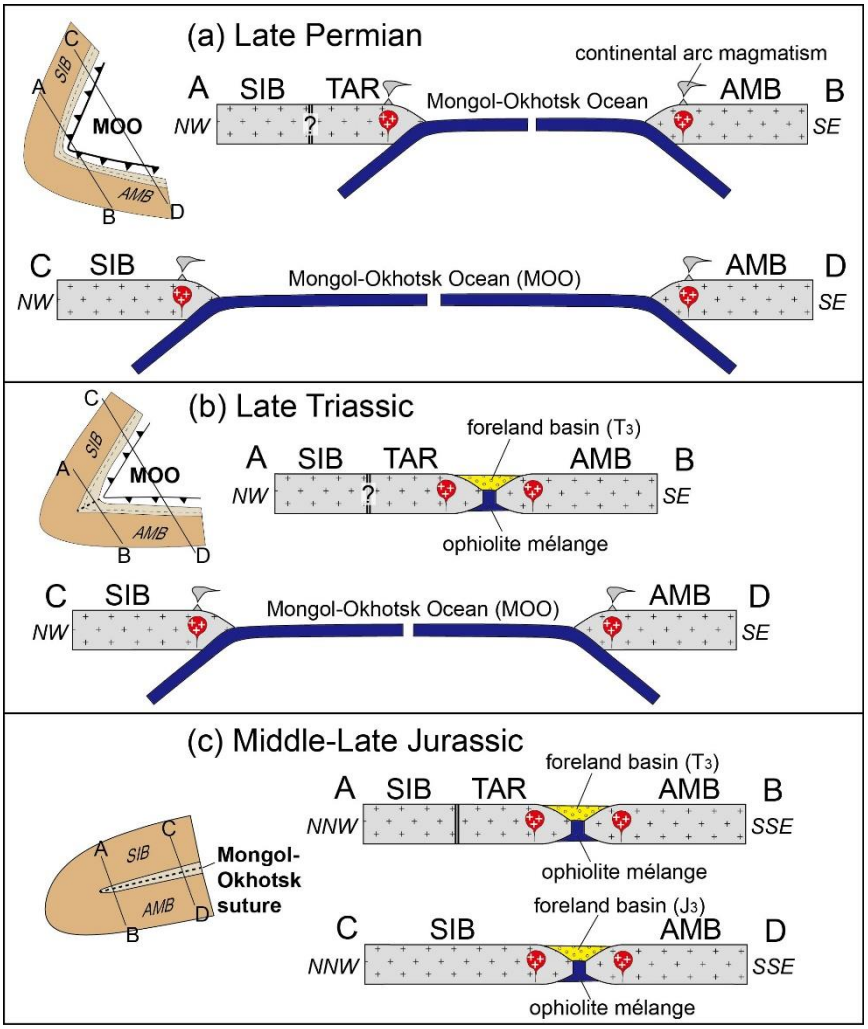

Figure 9. Bidirectional subduction and closure model of the MOO. (a) Late Permian: Bidirectional subduction of the Mongol-Okhotsk oceanic slab beneath the southern margin of the SIB and northern margin of the AMB. In the western segment, the Mongol-Okhotsk oceanic slab subducted beneath the Tarvagatay Block (TAR). (b) Late Triassic: Collision between the TAR and AMB caused closure of the western segment of the MOO; Bidirectional subduction of the Mongol-Okhotsk oceanic slab continued in the eastern segment. (c) Middle-Late Jurassic: Closure of the MOO in its eastern segment. Cartons in the left show relative orientations of both the SIB and AMB in different periods (based on paleogeographic reconstruction in Van der Voo et al., 2015). The cross-section A-B is located in the Khangay section and the cross-section C-D is located in the Ergun section of the Mongol-Okhotsk suture.

5. Problems and opportunities about paleomagnetic studies on the evolution of the

MOO

As a quantitative method constraining paleolatitude and paleogeography of plates, paleomagnetism can play an important role in the study of evolution of the MOO. However, paleomagnetic studies on the evolution of the MOO are insufficient and showing inconsistent or even contradictory results, resulting in the hot debate on this subject. Here, we will analyze possible reasons for this problem and hope this can contribute to the future paleomagnetic studies on the evolution of the MOO.

5.1 Problems about paleomagnetic constraints on the initial closure of the MOO

The initial closure of the MOO in its western segment is the consequence of collision between the northwestern margin of the AMB and Western Mongolian Blocks (Tuva-Mongolia Block and Tarvagatay Block) along the southern margin of the SIB. Available sedimentological and magmatic evidence supports a Late Triassic initial closure of the MOO (Badarch et al., 2002; Wang et al., 2022). However, as there is no Mesozoic paleomagnetic data reported from the Tuva-Mongolia Block and Tarvagatay Block to the north of the suture, or from the AMB to the south of the suture, paleomagnetists used data from the SIB and NCC to constrain the evolution of the MOO and reached a conclusion that the MOO closed simultaneously in the Late Jurassic-Early Cretaceous from west to east (Enkin et al., 1992; Van der Voo et al., 2015). The precondition for this kind of paleomagnetic comparison is that the Tuva-Mongolia Block and Tarvagatay Block stay at the southern margin of the SIB ever since their accretion to the SIB in the Neoproterozoic-Early Paleozoic. However, recent paleomagnetic studies show that after the accretion to the southern margin of the SIB, the Western Mongolian Blocks coevolved with the SIB for a short-time period, and rifted from the SIB since the Silurian and drifted away from the SIB (Kilian et al., 2016). Since the Late Silurian, the SIB drifted northward to high latitude, whereas the Western Mongolian Blocks moved southward to low latitude (Kilian et al., 2016) and reached ca. 25° N during the Late Carboniferous (ca. 315 Ma) close to the AMB (Ren et al., 2021). Due to the lack of Permian paleomagnetic data, the Permian paleoposition of the Western Mongolian Block cannot be constrained. However, as the Late Triassic paleolatitude of the Tarvagatay Block was at 32.8 ± 16.8° N, indicating that the Western

Mongolian Blocks still located in low latitude in the Late Triassic (Pruner, 1992). Our new Late Triassic paleomagnetic results confirmed that the Tarvagatay Block located in the paleolatitude of 30-35°N during the Late Triassic, consistent with that of the AMB, suggesting that the western segment of the MOO should have closed in the Late Triassic (Zhao et al., 2023).

Therefore, for initial closure of the MOO, one should compare paleolatitudes of the AMB with Western Mongolian Blocks directly rather than with those of the SIB. Future paleomagnetic studies can focus on the Tuva-Mongolia Block and the Tarvagatay Block. From newly obtained Late Paleozoic and Triassic paleomagnetic data, one can constrain the drifting history of the Western Mongolian Blocks and further discuss initial closure of the MOO. Meanwhile, if the Western Mongolian Blocks stayed in low latitude during the Late Paleozoic and Triassic, there must be a big latitudinal difference between the Western Mongolian Blocks and SIB in this period. Does this mean that there was an oceanic basin between them (an independent oceanic basin or a branch of the MOO)? This will be another subject for the evolution of the MOO.

5.2 Effect of the true polar wander (TPW) on the final closure of the MOO

The TPW is due to the reorganization of Earth mass during Earth rotation resulting in rotation of the crust and mantle relative to the liquid outer core. Plates show rapid latitudinal drift and relative rotation during the TPW (Evan, 2003; Steinberger and Torsvik, 2008; Kent and Irving, 2010). The TPW event in the Jurassic resulted in a global clockwise rotation around an Euler pole at western Africa (0°N, 11°E; Steinberger and Torsvik, 2008; Creveling et al., 2012; Torsvik et al., 2012). This TPW was referred as the "monster shift" by Kent et al. (2015). As the SIB and eastern Asian blocks located far away from the Euler pole, the clockwise rotation during this TPW event can result in dramatic southward drift of these blocks (Muttoni and Kent, 2019; Yi et al., 2019; Fu et al., 2020), which will affect the evolution of the MOO. Li (1993) firstly applied the TPW theory to study movement of the NCC during 200-120 Ma and concluded that the Jurassic movement of the NCC was affected by this TPW event. Yi et al. (2019) reported a Middle Jurassic (174 Ma) paleolatitude of the NCC at 61.7° ± 9.1°N, consistent with that of the SIB. Therefore, they proposed that the MOO should

have been closed in the Early and Middle Jurassic boundary, and then the eastern Asian blocks moved southward rapidly about 25° to 36.6° ± 5.1°N in the Late Jurassic (157 Ma; Yi and Meert, 2020). However, Gao et al. (2021) reported three paleomagnetic poles (170 Ma, 165 Ma and 160Ma) from the Middle-Late Jurassic volcanic rocks in the northern margin of the NCC, which show no obvious latitudinal movement of the NCC, but the SIB moved southward rapidly during this period. This phenomenon was explained as a result of combined influence of the Jurassic TPW and evolution of the MOO (Gao et al., 2021). In the framework of the TPW, both the SIB and the NCC-AMB should move southward rapidly. However, due to the northward subduction of the Mongol-Okhotsk oceanic slab, the dragging force will pull the NCC-AMB northward, which will counteract the TPW-induced southward movement. Therefore, the NCC-AMB shows insignificant movement during this period (Gao et al., 2021). Meanwhile, the paleolatitudes of the SIB and NCC-AMB have already overlapped in the range of uncertainty at 155 Ma (Figure 8), indicating that the MOO should have closed or have limited width.

Note that based on the model of Kent et al. (2015), the "monster shift" occurred in the Late Jurassic-Early Cretaceous (160-140 Ma). Therefore, the Early-Middle Jurassic evolution of the MOO should not be affected by this true polar wander event. Due to the lack of paleomagnetic poles in the age of 160-140 Ma for both the SIB and NCC, we cannot evaluate whether the "monster shift" true polar wander affect the plate motions in East Asia or the closure of the MOO. In this case, further paleomagnetic studies are needed for blocks in East Asia. New high-quality Late Jurassic paleomagnetic poles with good age constraints will provide us opportunities to discuss the influence of this true polar wander event to East Asian blocks and closure of the MOO.

6. Conclusion

As the last main ocean that affected the amalgamation and tectonic evolution of northeastern Asia, the MOO separated the SIB to the north, the NCC-AMB to the south and the Western Mongolian Blocks (including Tuva-Mongolia Block, Tarvagatay Block etc.) to the west. The MOO experienced long-term evolution from the Early Paleozoic

to Mesozoic. The opening of the MOO can be traced to its early stage at the Early Paleozoic. The northward subduction of the Mongol-Okhotsk oceanic slab beneath the southern margin of the SIB initiated in the Silurian, whereas its southward subduction beneath the north margin of the NCC-AMB started in the Late Devonian, relatively later than the northward one. The bidirectional subduction of the Mongol-Okhotsk oceanic slab resulted in pulse arc magmatism, with three main peaks in the earliest Carboniferous, Late Permian and Late Triassic-Early Jurassic. In the Late Triassic, due to the collision between the AMB and the Western Mongolian Blocks, the ribbon-shaped Western Mongolian Blocks bended and caused the initial closure of the MOO in its western segment. Due to the clockwise rotation of the SIB and counterclockwise one of the NCC-AMB, the MOO showed a scissor-like closure pattern from west to east. The final closure of the MOO occurred in the Middle-Late Jurassic, leading to the formation of the Mongol-Okhotsk orogenic belt, which also resulted in the formation of the Mongol Orocline. Since then, the amalgamation of main blocks in the northeastern Asia has finished, and the northeastern Asian continent went into the intraplate evolutional stage.

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