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Subduction and closing evolutionary mode in western Xar Moron suture zone

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Abstract. The Xar Moron suture zone is located on the suture of North China Craton and Siberian Craton, which is one of the research hotspots in the Geoscience. In this paper, the western section of the Xar Moron suture zone is taken as the research object. Based on geological and geodynamic analysis, the tectonic and evolution stages of the study area were divided, the evolution model of the subduction and closure of the Paleo-Asian Ocean in the study area, the collision of plates and plates is established. The results show that Xar Moron fault is a suture, and there are obvious differences between the crustal structures on both sides of the fault, outcrop volcanic rocks are distinguished by high potassium calcium alkaline series and their magmatic source is a mixture of crust source and mantle source. The study area is divided into four tectonic evolution stages, C₂-P₂, P₂-P₃, P₃-T₃ and After T₃ stage. It is estimated that in the late Permian to early Triassic, Paleo-Asian Ocean has experienced the post-arc dilation, the arc-continent collision and the pre-arc accretion stage. It established the subduction and closing evolutionary mode of the Paleo-Asian Ocean in the Xar Moron suture zone, which provide a reference for the study of the dynamic mechanism of the formation of the fault zone.

Keywords: the Xar Moron suture; Crustal structure; Magma effect; Paleo-Asian Ocean; Evolutionary mode.



1. Introduction

The Xar Moron suture zone is a complex fault zone with a width of 20km and a length of more than a thousand kilometers. It passes through the Moho surface and belongs to the deep fault zone of the upper-lithosphere. The fault is on the suture zone of the North China Craton and the Siberian Craton [1-6], the suture zone in Inner Mongolia marks final closure of the Paleo-Asian Ocean and the termination of subduction accretionary activity [3; 4; 7; 8; 9]. The closure of Paleo-Asian Ocean is a topic of considerable debate and a variety of scenarios have been proposed. Because the large number of faults, thrusts and sutures throughout the area makes it extremely difficult to determine the exact sequence of events [10].

Although the general consensus is that final suturing took place between the late Permian and Early/Middle Triassic [1,11-17], not all workers agree. Estimates of the time of closure of the Paleo-Asian Ocean range from Late Silurian/Devonian [18-19] to Cretaceous [20], with some workers favouring the Middle to Late Devonian [21], the Late Devonian to early Carboniferous [22-23], the late Permian [1,15,24], the late Permian to Early/Middle-Triassic [3,7,11,16,25], or the Middle to Late Triassic [16,26]. Locating the terminal suture in a long-lived oceanic archipelago that involved double-sided subduction, the extensive development of island and continental arcs, accretionary prisms and ophiolites-and is relatively poorly exposed-is not an easy task, especially when there are abundant orogen-parallel strike-slip faults and suture zones. It is not the intention to discuss the intricacies of the various debates here; the purpose is simply to highlight that major uncertainties still exist. Orogen-parallel strike-slip faults and thrusts are common in the southern of Central Asian Orogenic Belt (CAOB) and establishing their timing is critical [10].

Based on paleontology, geophysical exploration, petrogeochemistry, isotope tracing and isotope chronology tests, previous studies have obtained a relevant understanding of the final suture position and age of the Siberian Craton and the North China Craton, especially the final closure time. However, the spatial distribution of the closure of the Paleo-Asian Ocean is still the focus of geologists' research for decades, and there is still much controversy about these geological problems, such as: (1) whether the Xar Moron suture belt is the final region of the closure of the Paleo-Asian Ocean, (2) how many tectonic evolution stages has the closure of Paleo-Asian Ocean experienced, and what is the structural pattern in each stage of different areas? In this paper, the western section of the Xar Moron suture zone is taken as the research object. Based on geological and geodynamic analysis, the evolution model of the subduction and closure of the Paleo-Asian Ocean in the study area, the collision of plates and plates is established, and the dynamic mechanism of the formation of the fault zone is provided as a reference.

2. Geological setting

In the northeast of China, south to north, there are mainly Xar Moron suture belts, Solonker suture belts and Hegenshan suture belts between the Siberian Craton and the North China Craton (Fig. 1) [27-29]. Different scholars have different definitions on the way and scope of the suture belt. To Paleo-Asian Ocean, there are several kinds of understandings about the era of final collision suture: Permian [3,15,30], Early Permian-Late Triassic [2], Late Permian [5,31], Middle Permian (~270Ma)-Middle Permian [32], Late Permian-Late Triassic [33], Triassic [25], etc.

When the main ocean basin disappears, the continental crust abutment reduction zone will be formed [34]. It begins in the Late Permian and reaches the late Triassic. The Paleo-Asian Ocean is closed and dying. The North China Craton and the Siberian Craton collide and overlap (crustal reduction). Most studies now show that the Paleo-Asian Ocean was closed at the end of the Permian-Late Triassic. Shao Ji'an et al. [35] realized that the Paleozoic-Early Mesozoic in the northern part of North China was in the Paleo-Asian tectonic domain and ancient times through the understanding of the magmatism in the Da Xinganling Mountains area in eastern Inner Mongolia. It is believed that the Paleozoic-early Mesozoic in the northern part of North China is in the superposition stage of the paleo-Asian tectonic and paleo-Pacific structural systems, after which the lithosphere entered the stage of extension and thinning. Based on the previous studies, Wilde [36] also believes that the superposition occurs at the end of the Permian-Early Triassic. The fact that the complexes of the eastern part of Inner Mongolia and

the ophiolites existed showed that the ancient oceanic crust had multiple subductions along the north and south continental marginal belts, and in the late Triassic period the ancient lands eventually collided [27].

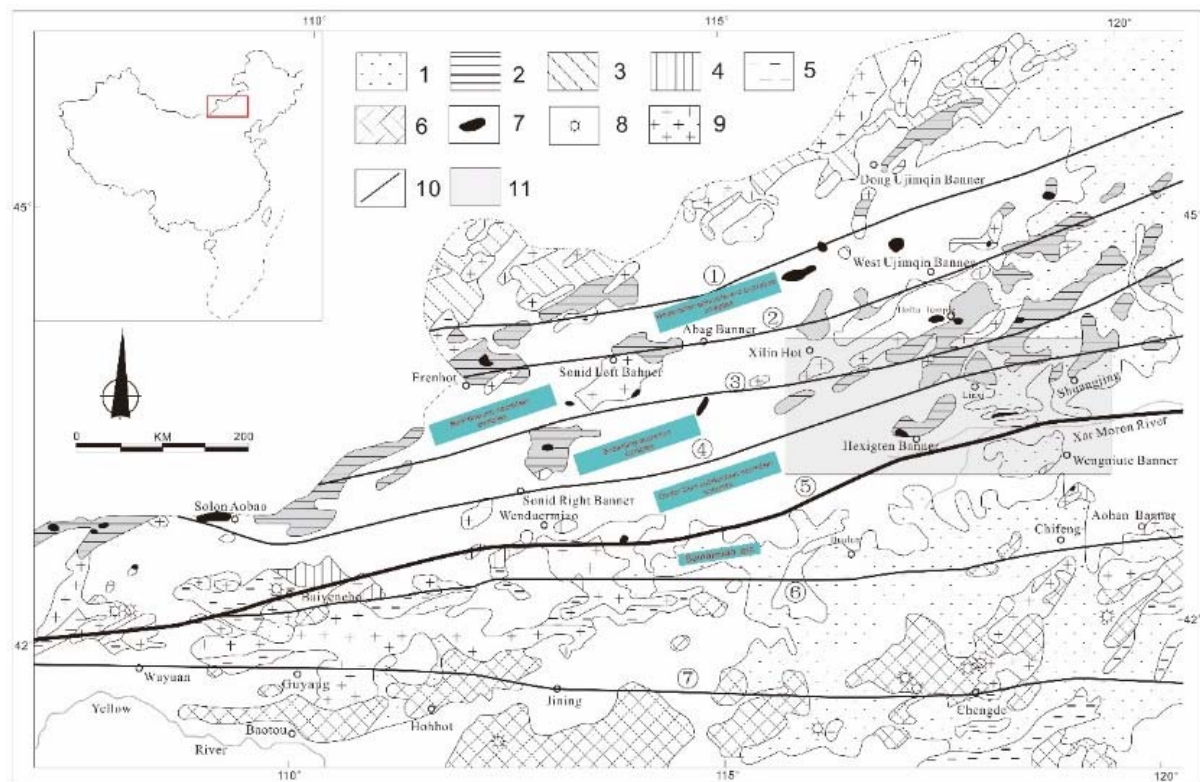


Figure 1. The mid and east geology diagram of Inner Mongolia (Organized by [6, 15, 27, 29])

1.Cretaceous 2.Carboniferous-Permian 3.Devonian 4.Cambrian-Silurian 5.Bayan Obo group-Zalta group of Mesoproterozoic 6.Substrate of Archean to Early Proterozoic 7.the Ophiopogon set 8.Alkaline Magmatic rocks 9.Paleozoic granite 10.Fault 11.Research area

Note:①Chagan Obo-Arongqi fault②Erenhot fault③Xilinhot fault④Linxi fault⑤Xar Moron suture⑥Chifeng-Bayan Obo fault⑦Jining-Longhua fault

Su Meixia et al. [37] found that there is a giant gravity and magnetic anomaly zone along the 42°N latitude zone, with the northern boundary being the Solon Mountain-Balinyouqi fault (F3) and the southern boundary Linhe-Jining fault (F5) in the northern margin of the North China plate. Between them is the Xar Moron suture(F4). Among them, F3 and F4 constitute the Solon Mountain- Xar Moron suture belt (referred to as the Xar Moron suture belt). The structural belt has a maximum width of more than 100 kilometers [38].

The north side of the giant gravity and magnetic anomaly zone is a low-positive anamagnetic anomaly zone and a low gravity zone. On the aeromagnetic anomaly map, it appears as a gently open and broad giant low-positive anamagnetic anomaly zone, which is nearly east-west intermittent or Continuous distribution. It is caused by the Late Paleozoic (late Carboniferous-Early Permian) calc-alkaline series volcanic rocks and I-type granites (dominated by late Variscan) distribution on the northern margin of the North China Plate. On the south side of the giant positive magnetic anomaly zone, there is a giant negative magnetic field arranged parallel to it. The magnetic anomaly zone corresponds to the gravity low value zone and is mainly characterized by a gentle negative magnetic anomaly. This anomalous zone is caused by the Late Paleozoic weak magnetic low-density S-type granite (dominated by late Variscan) closely associated with the I-type granite belt. Strong magmatic

activity and large-scale granite intrusion are important reasons for the formation of giant gravity low-value zones [37].

Lu Zaoxun et al. [39] found that the area is roughly distributed in the east-west direction of the Lower Paleozoic double metamorphic belt, the double magmatic rock belt, the ophiolite belt and the pre-arc hybrid accumulation, indicating that the north side is the Xar Moron suture-The Ondor Sum subduction zone subducts southward; the south side is the Wengniute Banner-Bainaimiao Island arc belt, which develops Caledonian granite. There are significant differences in seismic wave velocity distribution and crustal thickness between the crusts on the south and north sides. The top surface of the asthenosphere also undergoes obvious abrupt changes, which are shallow in the north and deep in the south, with a variation range of 50 km. Through a fine anatomical study of the seismic sounding profile (Fig. 2) of the Dandong-Dong Ujimqin section in the global geoscience transects (GGT). Zhang Zhenfa [40-41] believed the middle crust generally develops a low-velocity layer, while the structure of the upper crust and the lower crust and the composition, metamorphism and evolution process of each velocity layer are basically the same in the south of the Xar Moron suture. To the north of the Xar Moron suture, under the caprock of the Mesozoic and Cenozoic, as can be seen from the velocity of the strata, the Paleozoic unmetamorphosed and shallow metamorphic rocks in the upper and middle crust are extremely thick, and the low velocity layer is not seen in the middle crust. Until the lower crust, the Paleozoic stratum is thick, up to 30km. It can be seen from the figure that the Moho surface depth is 30~40km. In the seismic section, the low-velocity layer corresponds to the high-value anomaly area of the electrical section and the low-density anomaly area of the two-dimensional interpretation section of gravity anomaly. These anomalous areas are likely to be the distribution areas of underground potential magma chambers.

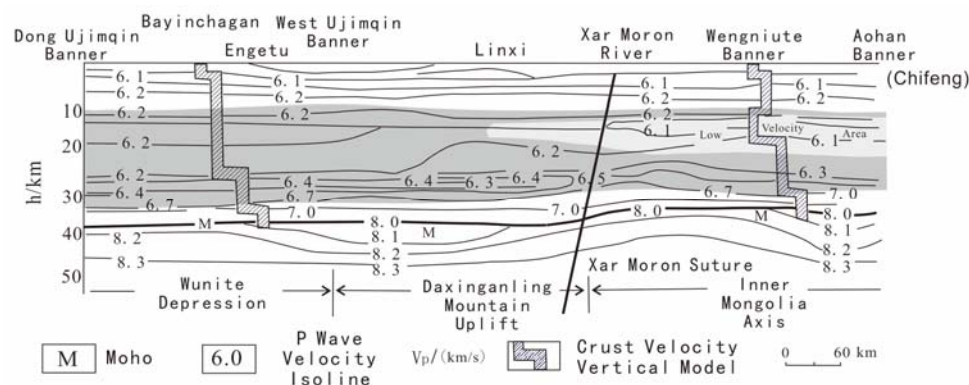


Figure 2. Crustal Structure of Aohan-East Ujimqin Banner Seismic Profile (modified after [41]; Quoted from [39])

3. Regional Geology and Main Place-Time Units

Under the tectonic stress, with the formation and development of the fault system and the new fracture, the magma invades the new fracture system and even spurts the surface [42-44]. With the continuous action of crust and mantle, the asthenosphere and the upper mantle are partially melted, and the new magma is invaded into the lower crust, forming a lithospheric basal or sub-invasive action. As the magma channel fault system and the bottom and bottom intrusion continue to expand, some plots or fragments of the lower crust will be disintegrated. Due to the interaction and mixing of the chemical substances brought by the magma with the lower mantle, mechanical thermal and chemical erosion or partial disintegration of the upper part of the asthenosphere up to the lower crust is caused, resulting in a significant reduction of rock rafts [45-48]. Therefore, as the crust-mantle interaction progresses and the stretching increases, the magma in the outer mantle column of the earth enters the asthenosphere at the place where the extension strength is the greatest, and continues to invade the lithosphere, resulting in a wide range of active extension of the lithosphere, producing mid-ocean ridges, and then forming the ocean basin [49].

Wang [27] believes that the north of Chifeng can identify and classify five accretionary complexes, and namely Wengniute accretionary complexes band, Linxi accretionary complexes band, Haoertu Temple accretionary complexes band, West ujimqin accretionary complexes band and Dong Ujimqin accretionary complexes band. They are all not "exotic" geological bodies, but products of continental marginal hyperplasia. These accretionary complexes are divided by faults, and there are ophiolites along the faults. The Wengniute accretionary complexes band and Linxi accretionary complexes band these two accretionary complexes are the product of the northward extension of the Sino-Korean paleocontinent, while the remaining three complexes are the result of the southward expansion of the Siberian paleocontinent.

The contemporary double-sided subduction beneath North China and the Mongolian Arc Terranes, as well as simultaneous intraoceanic subduction, led to the final closure of the Paleo-Asian Ocean in the Late Permian [50]. The study area, roughly along the SE-NW direction, shows the tectonic evolution of the Early Carboniferous-Late Carboniferous-Early Permian-Middle Permian-Late Permian-Triassic strata (Fig. 3). A ~630 km-long deep seismic profile across the Xar Moron suture zone was undertaken as part of the SinoProbe Project [51] and reveals a broad divergent symmetry, with north-dipping thrust systems to the south of the Solonker suture zone and southdipping reflectors to the north of the suture zone; consistent with geological observations across the region. However there are no convincing traces of fossil subduction zones in the underlying mantle [36]. Combined with the research theory of multi-island arc basin and continental hyperplasia [52], the subduction of the Paleo-Asian Ocean closed and died. From the Early Permian to the Late Triassic, it experienced post-arc expansion, arc-land collision and pre-arc hyperplasia, eventually the ocean closed and orogeny. In this paper, we argue that the subduction of the Paleo-Asian Ocean until the closure has experienced several gradual stages of growth: post-arc expansion, arc-land collision, pre-arc hyperplasia. In the Xar Moron suture zone, from the end of the Permian to the Late Triassic, the Paleo-Asian Ocean passed through a series of complex oceanic-continental and continental-continental tectonic movements, eventually disappearing (shown in Fig.4), and the Ondor Sum subduction-Proliferation complexes and the Bainaimiao Island arc [15,53], the Linxi fault and the Chifeng-Baiyun Obo fault, especially the ophiolite near the Chifeng and the ophiolite belt near Linxi. It is verified that the Paleo-Asian Ocean experienced strong evidence of post-arc expansion and arc-land collision.

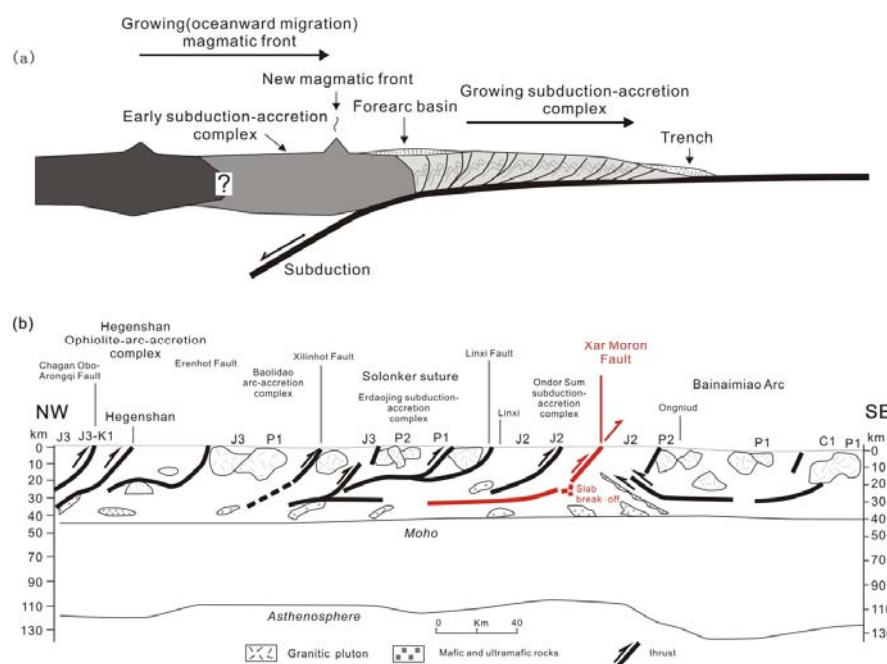


Figure 3. Tectonic model for migrates oceanward and tentonic characteristics showed on section from Hegenshan to Ongniud

(a) A tectonic model to show the overlap of magmatic arcs and subduction-accretion wedges as a magmatic front (active arc) migrates oceanward (modified after [15,62]); (b) cross section from Hegenshan to Ongniud. The deep structure is based on the interpretative geophysical section of [39], and the surface structure is based on [15,24,27,51,63-65]

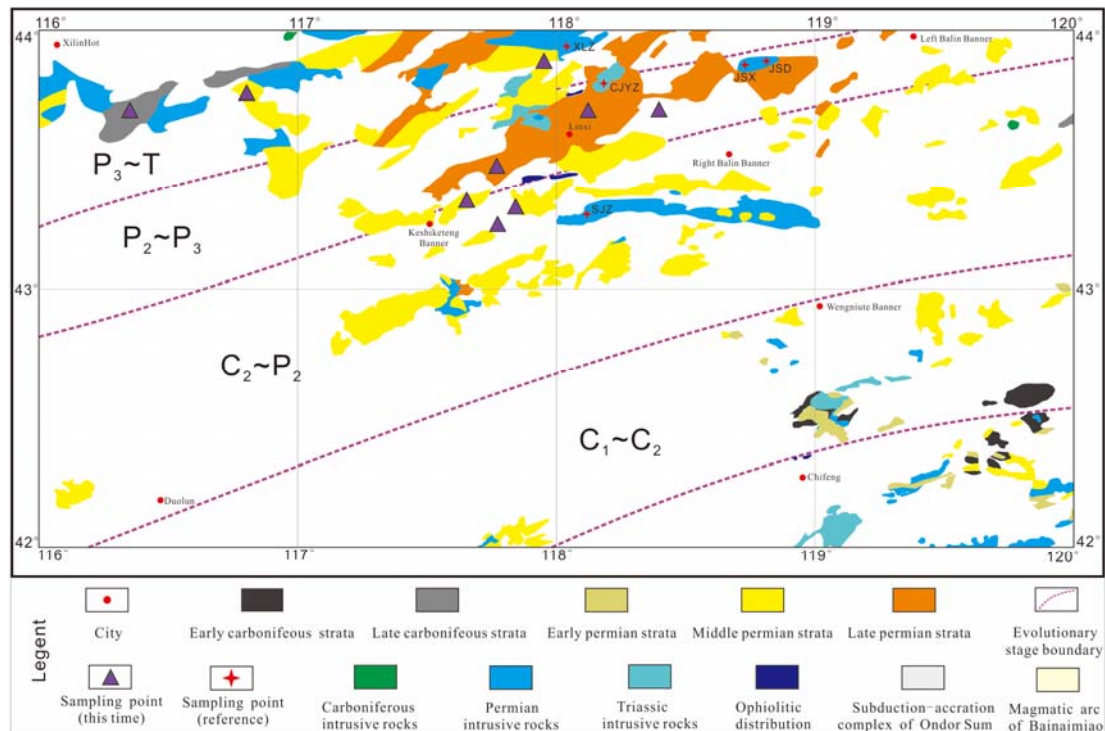


Figure 4. Field outcrops distribution of Carboniferous to Permian in the research area (Modified by 1:1000000 geological map-K50 Zhangjiakou picture frame)

Note: XLZ, Xinlinzhen pluton; CJYZ, Chuangjiayingzi pluton; JXD, Jianshedong pluton; JSX, Jianshexi pluton; SJZ, Shuangjingzi pluton

The Solon suture zone is from the Solon Mountains ophiolite belt in the west. Due to the east of the Soron Mountains, the ophiolite is widely distributed. The ophiolite is thought to be formed on the subduction zone [54-56], some researchers believe that the Solon suture zone extends eastward to Hegenshan [11,24,57], and some believe that it should be extended to Xar Moron River [53,58-60]. the Paleo-Asian Ocean began in the Ordovician and Silurian periods, and the oceanic Craton began to move, and the Late Permian to Early Triassic closed here. The Xar Moron suture zone is located in the southeastern part of the Solon suture zone. The southern boundary is roughly located in the Bainaimiao Island arc and the Ondor Sum complex, northward to the north of the Linxi fault. The subduction and extinction of the Paleo-Asian ocean occurred in the Xar Moron suture zone later than the solon suture zone, which started in the late Permian and finally closed around the early Triassic [5,32-33]. Difference in temperature caused by different thermal events may be an important reason for differences in geophysical fields [61]. Based on the research in the study area, the reduction and closure mode of the Paleo-Asian Ocean in the Xar Moron suture zone is established.

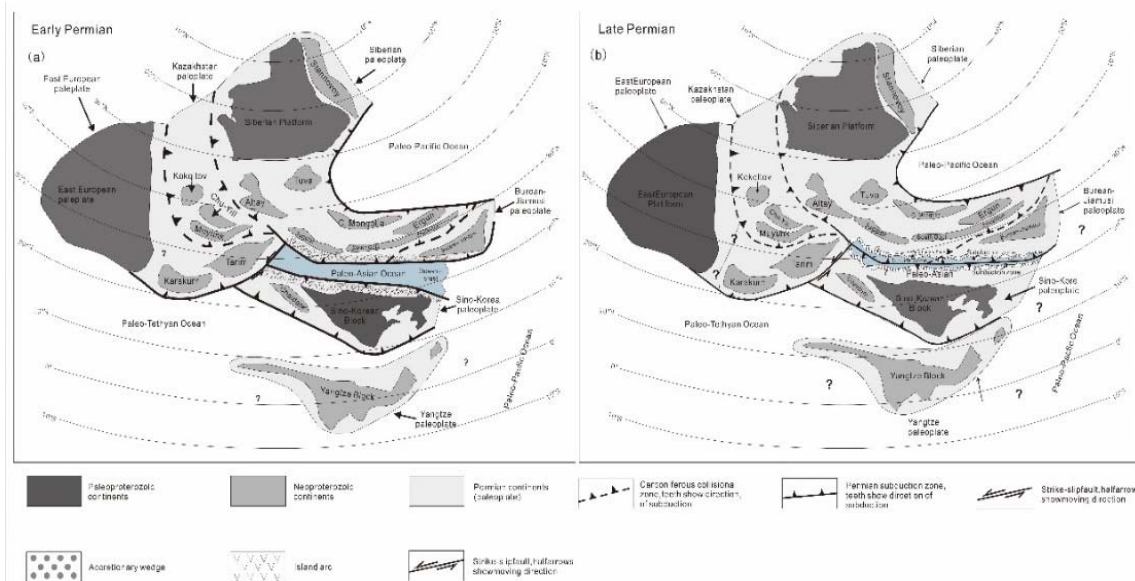


Figure 5. Palinspastic reconstruction of Permian ocean-continent framework of Northeast China and adjacent regions. (Modified by [15, 59])

Note: Interrogation marks on the map show areas where the Early Permian tectonic setting is not clear.

Combined the previous research results in the Fig.3 with the results shown in Fig.5, the closure of the the Xar Moron suture experienced the plough thrust in the NW-SE direction, which may be the result of the magmatic activity in the upper crust caused by the subduction of the Paleo-Asian Ocean plate to the North China Craton. The study of palinspastic reconstruction of Permian ocean-continent framework of Northeast China and adjacent regions (Fig. 5), suggests that the whole section represents a northward growing accretionary complex which may have been resulted from seaward retreat (northward) of a south dipping trench along which the Paleo-Asian ocean was subducted beneath the north China craton in the Late Paleozoic [15]. According to Xiao et al [15], the suture may be better interpreted not as a single line, but as a multiple suture zone within the accretion complex, it can also be understood that the formation of suture bands is the result of the superposition of multiple tectonic movements.

4. The tectonic evolutionary model in research area

Five major tectonomagmatic episodes have been identified along the Solonker-Xar Moron suture zone in response to progressive closure of the Paleo-Asian Ocean and final amalgamation of the Central Asian Orogenic Belt (CAOB) [3,4,8,9,48,66,67]: (1) the Late Carboniferous-Early Permian (329-273 Ma), with an active continental margin, development of the back-arc basin, slab rollback, and emplacement of the Solonker-Xar Moron ophiolite; (2) the middle-Late Permian (270-259 Ma), with initial collision between the South Mongolia Terranes and the North China Craton, termination of marine sedimentation, and only weak magmatism; (3) the latest Permian-Early Triassic (255-250 Ma) (Table 1), which was the collisional orogeny stage with linear magmatism, slab break-off, and intermediate P/T greenschist-blueschist facies metamorphism; (4) the Early-Middle Triassic (251-235 Ma) (Table 1), when intracontinental contraction occurred with tectonic shortening and thickening; and (5) the Late Triassic (230-200Ma), which was the postorogenic stage with emplacement of A-type granite and metamorphic core complexes. Because Archaean-Early Proterozoic rocks occur on both sides of Jining-Longhua fault, we prefer to use the Chifeng-Bayan Obo fault (fault⑥ in Figure 1) as the northern boundary of the Precambrian north China craton [15, 64, 68-70].

Table 1. Sample locations and Th/U and Age of the igneous rocks within the Xar Moron Suture zone

No.	Sample	Location	Lithology	Th/U	$^{206}\text{Pb}/^{238}\text{U}$ Age(Ma)	From
1	11XL-4.1	Xinlinzhen pluton	Granodiorite	0.30~1.34	251 ± 3	[9]
2	LX913-10	Chuangjiayingzi pluton	Monzogranite	0.24~0.56	245 ± 3	
3	XF915-4.1	Jianshedong pluton	Tonalite	0.39~0.91	250 ± 2	
4	11XF-6	Jianshexi pluton	Granodiorite	0.46~1.20	245 ± 4	
5	11SJ-03	Shuangjingzi pluton	Granite	0.60~1.20	248±1	

On the northern side of the Chifeng-Bayan Obo fault is the Mid-Ordovician to Early Silurian Bianaimiao arc [71], which contains calc-alkaline tholeiitic basalts to minor felsic lavas, alkaline basalts, and agglomerates, volcanic breccias, tuffs, granodiorites, and granites. In Bainaimiao village granodiorite, quartzdiorite, and homogeneous hornblende gabbro are intruded by feldspar quartz porphyry and veins of aplite. To the north of Bainaimiao a melange at Ondor Sum which is called Ondor Sum subduction-accretion complex, with high-pressure phases include ferroglaucofanite-crossite, riebeckite, lawsonite, phengite, pumpellyite, aragonite, jadeitic pyroxene, and stilpnomelane. Lawsonite occurs mainly in the cores of pillows and decreases in abundance outward. The pillow matrix has the assemblage calcite-haematite-quartz-lawsonite. Quartzitic mylonites contain glaucophane, stilpnomelane, deerite, minnesotaite, and piedmontite [15].

Most geodynamicists agree that the plates move because of the sinking of lithosphere in subduction zones [72-74]. Through the study of the high Sr/Y granitoids in the north of the Solonker-Xar Moron suture zone and the northern accretionary orogen, Li et al. [9] indicate that the source region north of the central Solonker-Xar Moron suture zone was dominated by juvenile components, whereas the area south of the central Solonker-Xar Moron suture zone was dominated by older components. These characteristics further support the view that terminal collision occurred along the central Solonker-Xar Moron suture zone [3,8,4,67].

5. The subduction and closure evolutionary mode in research area

From the geological and geophysical evidence in the study area, the evolutionary pattern of the Paleo-Asian Ocean from the Late Permian to the end of the Early Triassic was revealed. During the Carboniferous to Early Permian (329-273 Ma, the first episode), tectonic activity continued with subduction and arc formation along the Solonker-Xar Moron suture zone [e.g., 3,4,9]. The latest Early Permian (277-275 Ma) magmatism was a response to the last magmatic episode of a prolonged magmatic flare-up, from the Late Carboniferous to Early Permian in this area [9,75]. During the Late Carboniferous to the Middle Permian (C₂-P₂), especially since the early Permian, the Siberian Craton moved along the SE direction relative to the North China Craton, and the Paleo-Asian oceanic crust subducted to the North China Craton, forming the Bainaimiao Island Arc. Arc magmas were thought to result from frictional melting of subducted crust and sediments along the subduction interface [74]. The subduction movement caused the lower crust delamination and to be dehydrated, and under the action of strong tectonic movement, part of the rock inside the lithosphere melted at a high temperature, forming a magma upwelling or even erupting to the ground. Around the Middle Permian, the relative movement near the Wengniute Banner was temporarily slowed down, and at the same time, under the action of subduction and compression, the fold belt and the accretionary complex belt are formed. During this period, the Wengniute accretionary complexes belt was formed, and the proliferating complex appeared at the junction of the ocean and the continent (Fig. 6(a)). During the Middle Permian to the Late Permian (P₂-P₃), the relative movement of the Siberian Craton was strong and the collision between the ocean and the land was intense, forming many slabs which were broken off from dehydration of subducted crustal materials or oceanic crust. Indeed, in most cases, the mafic rocks within ultrahigh-pressure terranes are part of the continental crust, rather than representing slices of oceanic crust [76-77]. This tectonic movement forms the Linxi hyperplasia zone and a large-scale strip-like distribution of the Ondor Sum subduction-proliferation complex (Fig. 4). Meanwhile, the ophiolite associated with the oceanic subduction was exposed on the ground. Around the Late Permian, the

tectonic movement tends to be slow (Fig. 6(b)). Upon collision, seafloor subduction stops, but convergence continues for some time, during which the last fragments of underthrust ocean crust probably remain at depth [e.g., 9, 78], while the partially broken slabs melt at high temperatures and move upward with magmatic activities. During the Late Permian to Late Triassic (P_3 - T_3) period, the ocean continent subduction occurred strong tectonic movements again near the Linxi, marked by the appearance of ophiolites. At the same time, it formed Linxi Fault^④ (shown in Fig. 1) due to strong tectonic movement. (Fig. 6(c)). The bidirectional subduction of the Paleo-Asian Ocean led to its final closure. (Fig. 6(d)). Around the Late Triassic, after the disappearance of the Paleo-Asian Ocean, the crustal movement did not stop, and the orogeny and post-orogeny were still ongoing, which was part of the central orogenic belt (CAOB), and the research on it was still in progress.

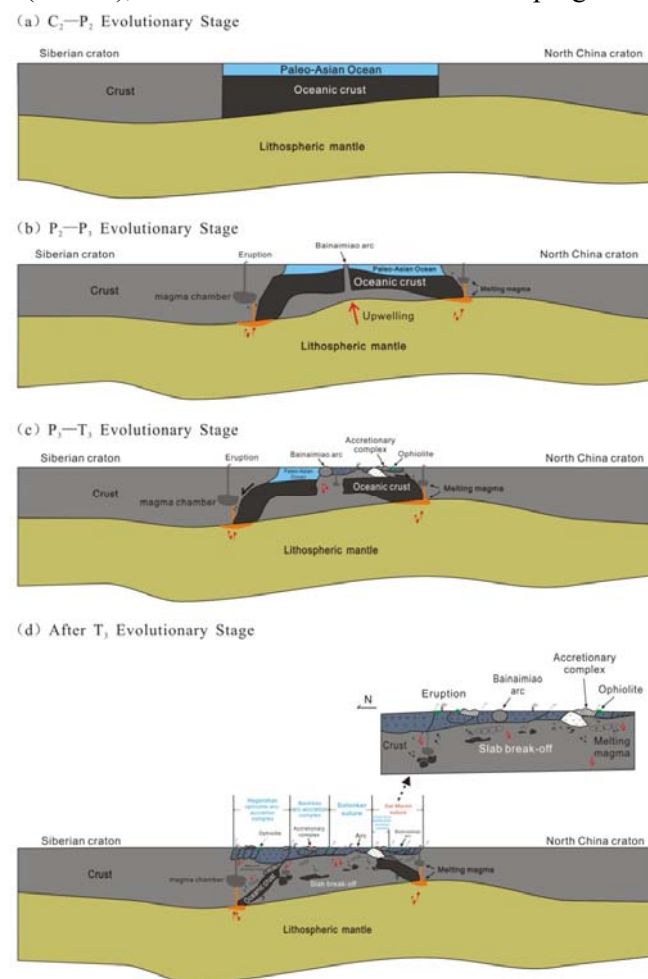


Figure 6. The subduction and closure mode of the Paleo-Asian Ocean in the Xar Moron suture

6. Conclusion

1. The crust structure on both sides of the Xar Moron suture is obviously different, based on outcrop volcanic rocks and geological analysis, the study area is divided into four tectonic evolution stages, C_2 - P_2 , P_2 - P_3 , P_3 - T_3 and After T_3 stage these four tectonic evolution stages.

2. It is estimated that in the late Permian to early Triassic, Paleo-Asian Ocean has experienced the post-arc dilation, the arc-continent collision and the pre-arc accretion stage. It established the subduction and closing evolutionary mode of the Paleo-Asian Ocean in the Xar Moron suture zone, which provide a reference for the study of the dynamic mechanism of the formation of the fault zone.

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