Geochronological data and paleontology of early Paleozoic terranes in Inner Mongolia: indicating the evolution of the southeast Central Asian orogenic belt

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Key Points:

- Newly identified Ayadeng Formation from Bayan Obo Group, and confirm it formed in the Early Ordovician through detrital zircon U-Pb age and paleontology
- The Ayadeng Formation might be an original stratum in Bainaimaio arc and formed in an extensional setting, while the Xibiehe Formation formed in a collisional setting
- The Bainaimiao arc might be an exotic terrane attached to the North China Block between 440-420 Ma

Abstract

In this study, we present detrital zircon U-Pb dating and paleontological data for the newly identified Ayadeng formation in the northern margin of the North China Block (NCB) and Xibiehe formation (molasse) in the Bainaimiao Arc Belt (BAB), which could provide strong evidence indicating the affinity of the BAB and the evolution of the southeast Central Asian orogenic Belt (CAOB). Zircon U-Pb data of siltstone samples and paleontological data indicate the Ayadeng formation dates back to the early Ordovician. Although its location is near the NCB, its zircon grains's age spectra and paleontology share a closer affinity with those of Tarim and NE Gondwana, as the U-Pb data suggest an age range of 778-1235 Ma, and similar gastropod fossils are found in Tarim and NE Gondwana. The U-Pb ages of meta-sandstone samples in the Xuniwusu formation indicate a shared inheritance with the Ayadeng formation (before 440 Ma), and the U-Pb ages of sandstone samples in the Xibiehe formation are concentrated, with age peaks centered at ca. 420Ma. Fossil corals occur in these two formations, and their sedimentary facies also indicate a collisional setting. Therefore, it is speculated that the BAB rifted from Tarim or NE Gondwana during the Ordovician and became attached to northern NCB between 440-420 Ma as an exotic terrane. During the early Paleozoic, there may have occurred a collision between an arc and a continental block.

Key words: detrital Zircon; paleontology; Bainaimiao Arc Belt; North China Block

1 Introduction

The Central Asian Orogenic Belt (CAOB), or Altaids, is one of the largest Phanerozoic orogenic systems. It is located between the North China Block (NCB) and Tarim (TA) to the south, and the Siberian Carton (SC) to the north (Sengör et al., 1993; Jahn et al., 2000; Xiao et al., 2003; Windley et al., 2007; Wilde, 2015). This area has been of considerable interest to researchers in recent years, as it was formed via multiple stages of accretionary processes (including accretion of island arcs, oceanic islands, ophiolites and microcontinents) (Khain et al., 2003; Mossakovsky et al., 1993). The continental crust formation was initially triggered by the subduction of the Paleo Asian Ocean (PAO); this occurred during a long geological period from the Neoproterozoic to the late Permian/early Triassic (Bdadrch et al., 2002; Li et al., 2006; Xiao et al., 2010). Although researchers have made some progress in discerning the processes which formed the CAOB, such as the PAO closure (Chen et al., 2014; Xiao et al., 2015; Xu et al., 2013; Zhao et al., 2013), there remain many unresolved questions in this area, one of which concerns the formation of the arc belt. Arc systems are often host to significant magma activities, and they play an important role in accretionary orogeny formation (Xiao et al., 2010; Zhang et al., 2014). These magmatic arcs possess unique geochemical features which are indicative of their tectonic setting, and so previous studies into arc formation have been concentrated on igneous rocks and have tended to ignore sedimentary terranes (Jian et al., 2010; Qian et al., 2017; Zhang, et al., 2013; Bai et al., 2015). There is a need for more meticulous investigations on sedimentary strata within such arcs. This study examines such strata, which provide useful evidence for the evolution of the CAOB.

The Bainaimiao Arc Belt (BAB, also named Southern Orogen by some researchers) extends over 1300 km across southeast-central Asia, and is considered to be an early Paleozoic arc terrane buttressing the northern margin of the NCB (BGMRIM, 1991; Xiao et al., 2003; Jian et al., 2008). The two units are separated by an E-W trend fault, the Chifeng-Bayan Obo fault (Figure 1). The northern border of the BAB is flanked by the Xar Moron fault, beyond which lies the Ondor Sum subduction-accretion complex in the north (Tang and Yan, 1993). The relationship between the BAB and NCB is still a matter of considerable debate. Many previous studies have suggested that the BAB was a continental arc formed during the early Paleozoic period due to the southward subduction of the PAO (De Jong et al., 2006; Xiao et al., 2015; Zhang., 2013). Others consider it an island arc which has few affinities with the NCB and which was finally accreted onto the northern margin of the NCB during the late Silurian to Devonian periods (Chen et al., 2020; Zhang et al., 2014; Ma et al., 2019). To address these controversies and investigating the evolution of the southeast CAOB, we present zircon U-Pb dating and paleontological data of Paleozoic (meta-) sedimentary strata in the BAB and NCB. For this particular study, some new strata had been selected form Precambrian strata, which will present new evidence and interpretations in relation to the tectonic evolution of CAOB.

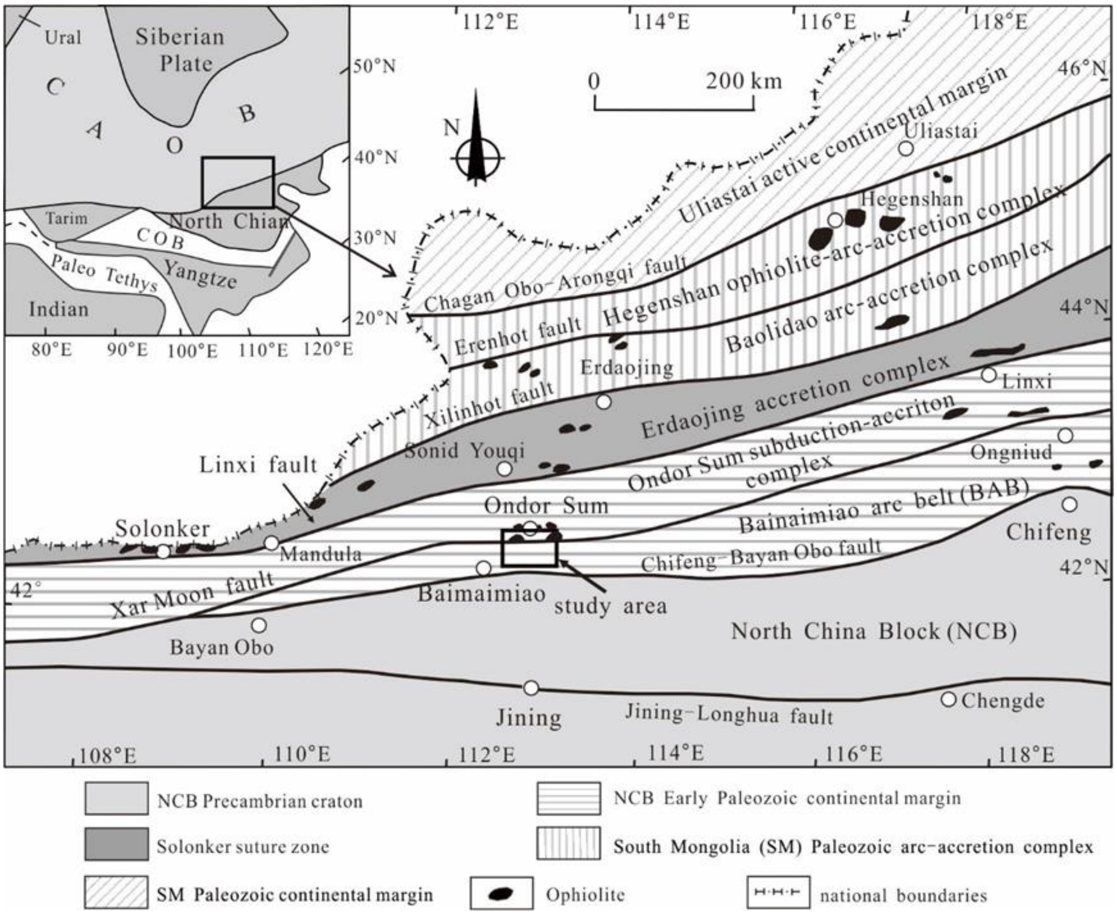

Figure 1. Simplified sketch map of the Central Asia Orogenic Belt (modified from Jahn et al., 2000) and a regional tectonic sketch of middle Inner Mongolia (Modified from Xiao et al., 2003)

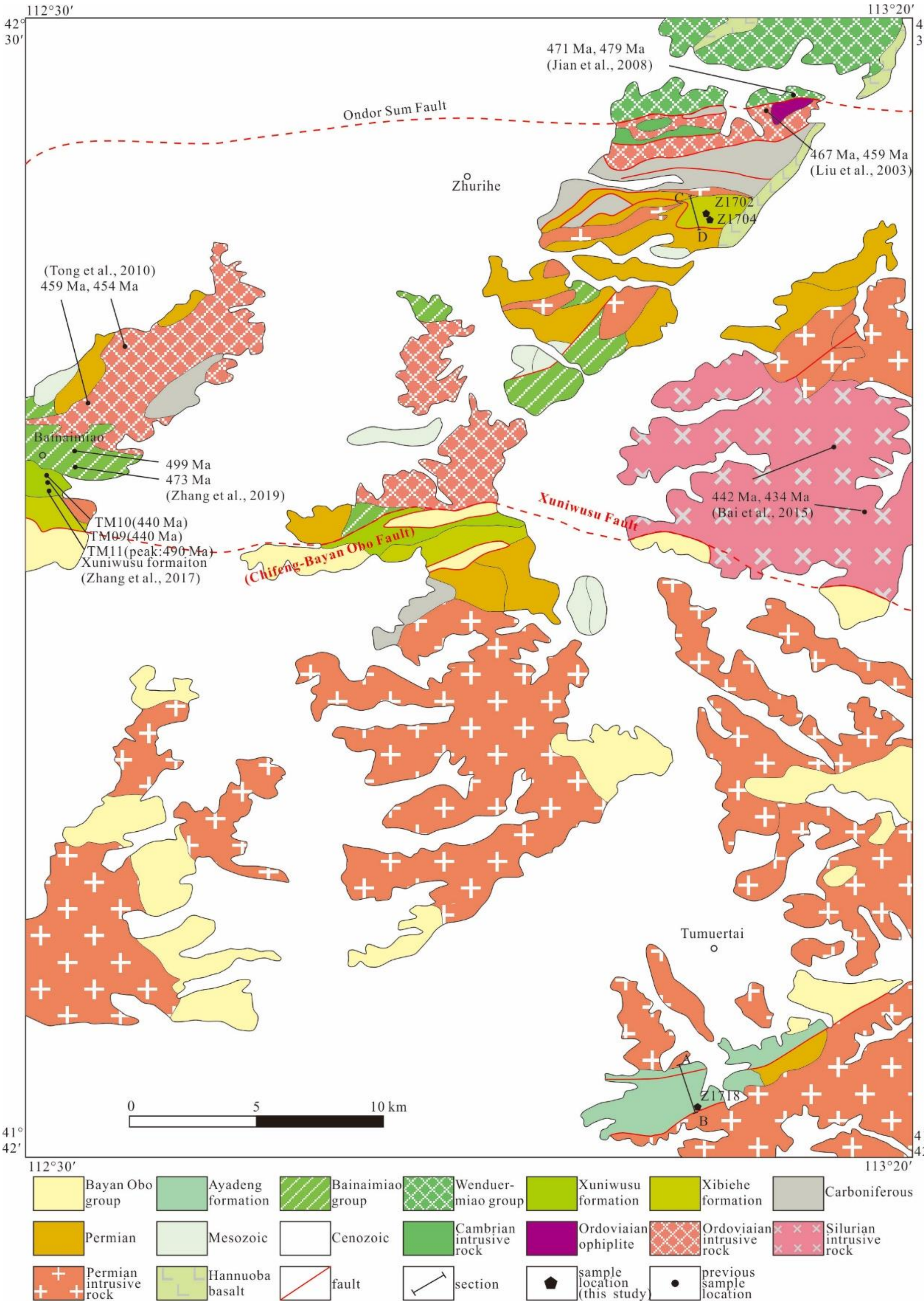

Figure 2. Simplified geological map of study area

2 Geological background

Our study area stretches over two tectonic units, the BAB and NCB, and the Chifeng-Bayan Obo fault cross the area (Figure 1 and Figure 2). Relatively, rocks and strata are well exposed in this area, especially igneous rocks. Ordovician, Silurian and Permian granite formations cover at least 40% of this area; these are intrusions into older rock units to a certain degree (Wang, 2014; Zhao et al., 2010). In this region, many geological units have been identified, including the Bayan Obo group, Bainaimiao group, Xuniwusu formation, Xibiehe formation, the Carboniferous to Permian volcanic-sedimentary formation, and the more limited Mesozoic volcanic formation (BGMRIM, 1991). The Bayan Obo group is mainly distributed in the NCB as a Precambrian formation, and is scattered in the southern and central parts of this area (Wan et al., 2011; Zhao et al., 2005). The Ayadeng formation, which has only recently been identified and mapped, and which is regarded as part of the Bayan Obo group in this area, is described below. The Bainaimiao group is composed of a greenschist-facies metamorphosed volcanic-sedimentary sequence, and is considered to have formed mainly in the Ordovician to Silurian periods (Zhang, 2013; Zhang et al., 2014). The Xuniwusu formation is composed of epi-metamorphic marine clastic rocks, crystalline limestone, and volcanic tuff, which unconformably overlies the Bainaimiao group. The Xibiehe formation is a molasse-type sediment consisting mainly of conglomerate and sandstone, which unconformably overlies the Bainaimiao group, Xuniwusu group and early Paleozoic granite (Zhang et al., 2017). The Carboniferous strata are dominated by the Jiujuzi formation, Amushan formation and Benbatu formation, which are scattered in the north (Lyu et al., 2019). By comparison, the Permian strata comprise the Sanmianjing formation and Elitu formation, which are distributed more uniformly. Limited outcrops of the Manitu formation and Baiyingaolao formation are exposed in this area, and these unconformably overlie the Permian granite stratum.

3 Petrography and sample descriptions

3.1 Ayadeng formation

The term Ayadeng formation was coined in the 1970s; this occurs within the Bayan Obo group. In view of its distinctive rock association and paleontology, which have been investigated in recent years, some researchers have suggested that it should be segregated from the Bayan Obo group and designated as an individual unit. The Ayadeng formation has been considered part of the Bayan Obo group in previous works, so we have undertaken detailed field work and chronological studies in an effort to redefine it.

A cross-section in this area is illustrated in Figure 3a. As the figure shows, the Ayadeng formation is divided into upper $[(\text{Є-O})_a^{2}]$ and lower members $[(\text{Є-O})_a^{1}]$. This does not comprise an intact stratigraphic sequence due to the top and bottom were faulted contact with the Bayan Obo group and Sanmianjing formation respectively. Moreover, Permian granite has intruded into this formation and produced marble near the pluton. As a result of intensive tectonic movement, folding, fracturing, so, epi-metamorphic rocks often appear in this formation (Figure 3a and Figure 3e). The lower member consists mainly of clastic rocks and limited limestone. The sandstones are inter-bedded with calcareous siltstone, and they share a nearly perpendicular alignment. The upper member is dominated by deformed and thick limestone (Figure 3a and Figure 3d), which contain some algal and animal fossils. In this study, we obtained some animal fossils (Figure 3c) and a siltstone sample (Z1718, 113°07'16″ E, 41°45'04″ N) for U-Pb dating. The siltstone is fine-grained (Figure 4a and Figure 4b; the medium-sized granules are generally less than 0.05mm), the calcium content is high, and the rock pore structure is complicated.

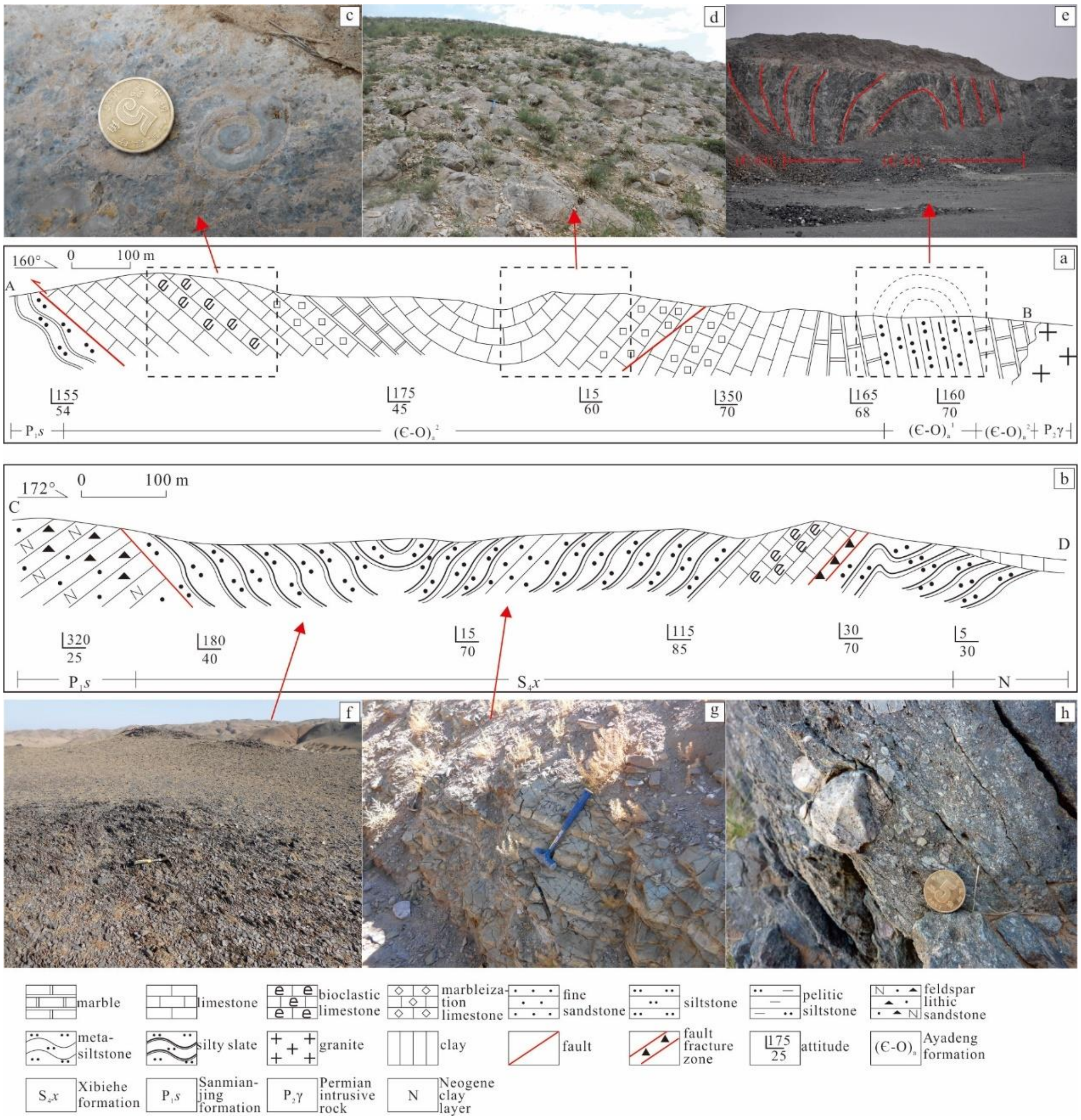

Figure 3. Geological sections and Field photos (a) section of Ayadeng Formation. (b) section of Xibiehe Formation. (c) bilclastic limestone. (d) thick limestone. (e) lower members of Ayadeng Formation. (f) silty slate. (g) sandstone. (h) conglomerate

3.2 Xuniwusu formation

The outcrops of the Xuniwusu formation are narrow, and only appear in the middle area in Figure 2. These have been the subject of previous chronological studies (meta-sandstone and meat-volcanic tuffs dated around 440.9 Ma) (Zhang et al., 2017), so it is not necessary to investigate them in this study. Zhang, et al. (2017) also plotted a cross section of the Xuniwusu formation. We tracked eastward along the limestone layer and have found some fossil corals. Due to subsequent destruction, the fossil corals are poorly preserved, and photographing and classifying them has proved difficult.

3.3 Xibiehe formation

Outcrops of the Xibiehe formation are scattered throughout this area, and mainly unconformably cover the Xuniwusu formation. A part of this formation is in contact with the

Sanmianjing formation via a thrust fault (Figure 2). In this study, we plotted a cross section (Figure 3b) in the north area in our study of the rock associations and fossils therein. This cross section is dominated by silty slate (Figure 3f) and some sandstone (Figure 3g). We did not find conglomerate in this cross section; however, it is very widespread to the east of this area (Figure 3h). We found some coral fossils in the limestone layer. In order to determine the age of this formation, we collected two samples (Z1702, Z1704, 113°08'54″ E, 42°21'58″ N) near the section for U-Pb dating. Sample Z1702 is magenta coarse sandstone (Figure 4c and Figure 4d). It contains unevenly distributed, rounded components, including detrital particles of quartz (~45%), feldspar (~30%) and debris (~15%); the rest is cement (~10%). Sample Z1704 is a gray-green fine sandstone with strong cleavage (Figure 4e and Figure 4f), the medium grain of which is generally less than 0.15mm.

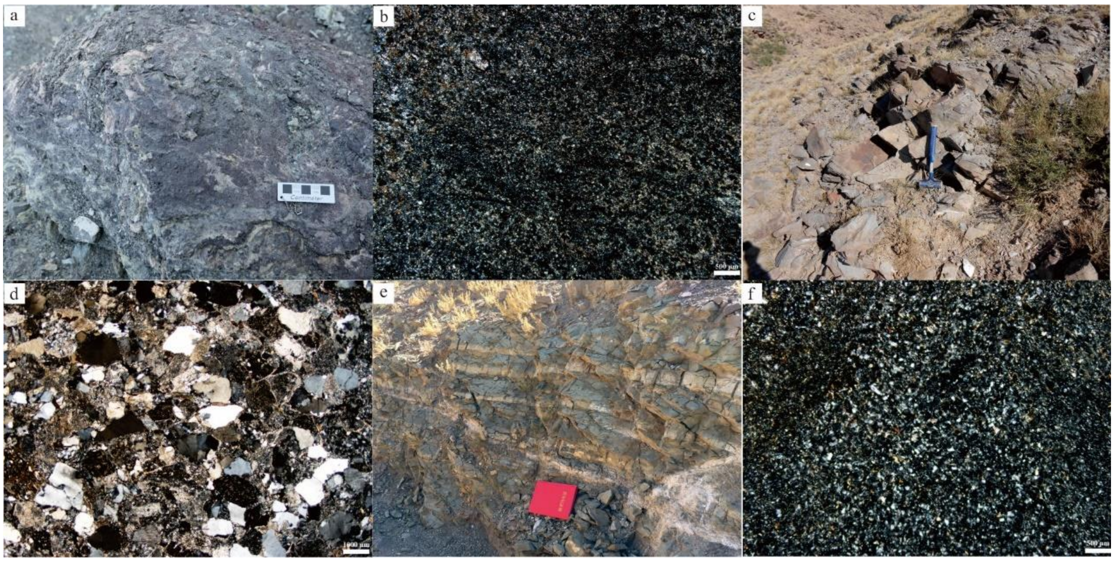

Figure 4. Representative outcrop and microphotographs of rock samples (a) and (b) Ayadeng formation Z1718. (c) and (d) Xibiehe formation Z1702. (e) and (f) Xibiehe formation Z1704

4 Paleontology

4.1 Ayadeng Formation

We collected several fossils in the upper member, including gastropods, cephalopoda and bivalvia. The most common fossils are gastropods, which are well persevered; by contrast, the cephalopda and bivalvia were damaged, and it was not possible to discern accurately their genus and species. The gastropod species consist mainly of *Ecculiomphalus* (Figure 5a and Figure 5b), *Pararahistoma* (Figure 5c and Figure 5d) and *Maclurites* (Figure 5e). Only one fossil was identified as a cephalopoda species, *Manchuroceras* sp. (Figure 5f), which existed during the early Ordovician to early Silurian periods. More detailed information on species classification of the fossils found in this study is provided in the table 1.

4.2 Xuniwusu Formation and Xibiehe Formation

All fossils found in Xuniwusu formation are corals. Due to poor preservation, it was not possible to identify their species. Four genera were identified in this study, including *Favosites*, *Heliolites*, *Mesofavosites*, and *Catenipora*. These date back to between the middle

Silurian and early Devonian.

Most fossils in the bioclastic limestone in Xibiehe Formation are well preserved, and corals make up a large majority of them. Species belonging to *Favosites* (Figure 5g) and *Heliolites* (Figure 5h and Figure 5i) can be identified in this formation; these existed during the Ludlow and Pridoli stages (S_3-S_4). Some *Chaetetes* fossils were found, but their species could not be determined. More detailed information is provided in the table 2.

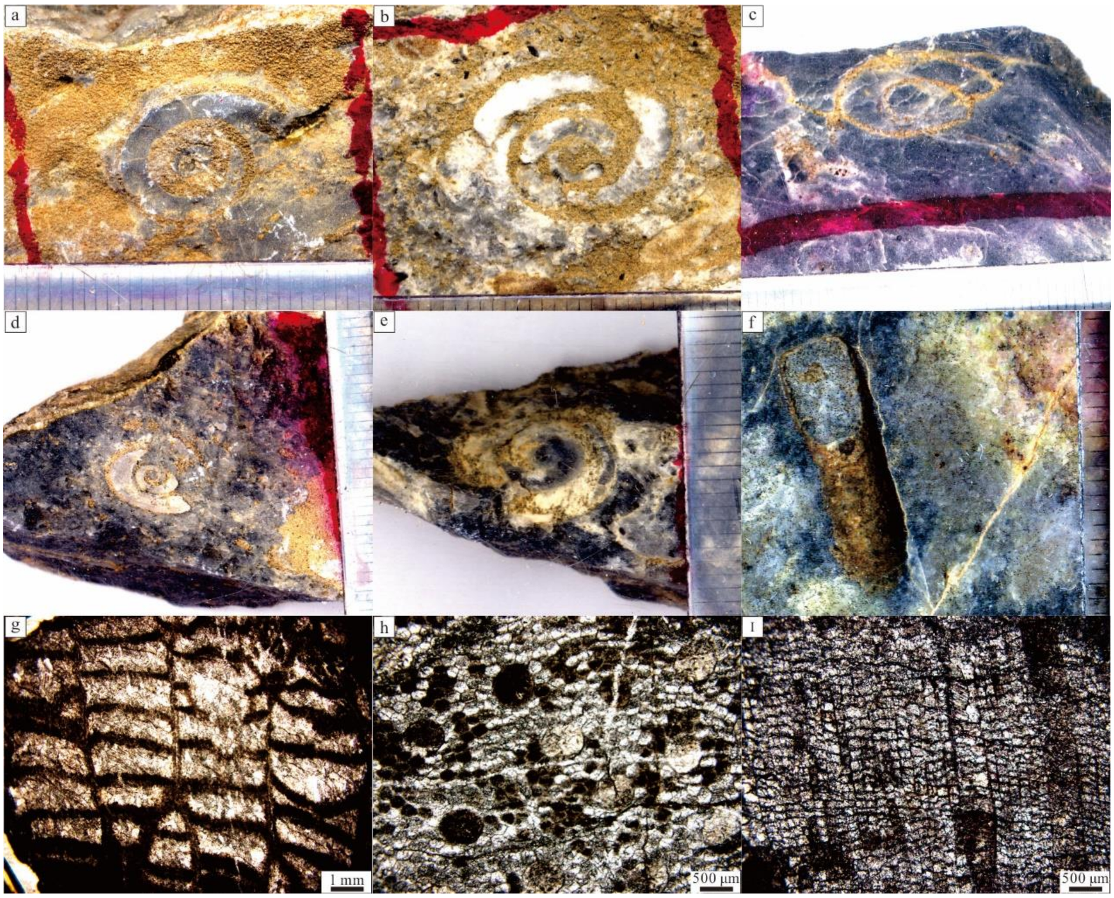

Figure 5. Photos of the fossil (a) *Ecculiomphalus kepintaghensis*?. (b) *Ecculiomphalus* sp.. (c) *Pararahistoma qualteriatum*. (d) *Pararahistoma* sp.. (e) *Maclurites zhuozishanensis*. (f) *Manchuroceras* sp.. (g) *Favosites favosiformis*. (h) and (i) *Heliolites insolens*.

Table 1. Era distribution of fossil in Ayadeng Formation(O_1, the early Ordovician; O_2, the middle Ordovician; O_3, the late Ordovician; S_1, the early Silurian)

Species and genus	O_1	O_2	O_3	S_1
Ecculiomphalus kepintaghensis?	---	---		
Ecculiomphalus sp.	---	---	---	
Pararaphistoma qualteriatum		---		
Pararaphistoma sp	---	---	---	
Maclurites zhuozishanensis		---		
Maclurites tofanggoensis		---		
Manchuroceras sp.	-----------	-----------	-----------	-----------

Table 2. Era distribution of fossil in Xuniwusu Formation and Xibiehe Formation (S_1, the early Silurian; S_2-S_3, the middle Silurian; S_4, the late Silurian; D_1, the early Devonian; D_2, the middle Devonian)

Species and genus	S_1	S_2	S_3	S_4	D_1	D_2
Favosites	----	----	----	----	----	----
Heliolites			----	----	----	----
Mesofavosites	----	----	----	----		
Catenipora		----	----			
Favosites. favosiformis			----	----		
Heliolites insolens			----	----		
Chaetetes sp	----	----	----	----	----	

5 Analytical methods and results

5.1 Zircon U-Pb dating

Zircon crystals were separated from whole-rock samples using conventional magnetic and heavy liquid techniques, and purified by hand-picking under a binocular microscope at the Langfang Regional Geological Survey, Hebei Province, China. The handpicked zircons were mounted in epoxy and polished to approximately half their thickness. They were then examined under transmitted and reflected light using an optical microscope as well as cathodoluminescence (CL) in order to reveal their internal structures. In accordance with CL images, distinct domains within the zircons were selected for isotopic analyses, which in turn were performed using an Agilent 7500a ICP-MS instrument equipped with a GeoLasPro 193 nm laser ablation (LA) system at the Key Laboratory of Mineral Resources Evaluation in Northeast Asia, Ministry of Land and Resources, Jilin University, China. Argon was used as the make-up gas and was mixed with the carrier gas via a T–connector prior to entry into the ICP. The analysis spots were 32 μm in diameter. Standard zircon 91500 was used as an external standard to normalize isotopic fractionation during analysis. The analytical procedures used follow those described by Yuan et al., (2004). The ICPMSDataCal (Ver. 6.7, Liu et al., 2010) and ISOPLOT 3.0 (Ludwig, 2003) methods were used for data reduction. Common Pb was corrected following the method set out by Andersen (2002). Uncertainties on individual LA-ICP-MS analyses are quoted at the 1σ level, with pooled uncertainties on ages given at the 95% (2σ) confidence level. And the LA-ICP-MS U-Pb isotopic data can be seen in supporting information Table S3 and Table S4.

5.2 Results of U-Pb dating

Siltstone zircon crystals extracted from Sample Z1718 are mostly euhedral-subhedral with fine-scale oscillatory growth zoning (Figure 6a). Most of them have relatively high Th/U ratios (>0.1); only one zircon (spot 35) had a lower Th/U ratio (0.04), which indicated that most of them are of magmatic origin (Koschek 1993; Belousova et al., 2002). Metamorphic rimmings were avoided during laser spotting, and a total of 70 zircon grains were analyzed, of which 65 passed the concordance filters (95%). Our U-Pb dating results indicate that age populations lie in the range of 1874-2192 Ma, with the major age peak centered at ca. 1935 Ma. Zircon grains with U-Pb ages of 490 Ma and 3248 Ma are the youngest and oldest zircon samples (Figure 7a), respectively. In addition, there are zircon samples which date back to the Neo-Mesoproterozoic (620-1627Ma), with major age peaks centered at 629 Ma, 788 Ma and 965Ma (Figure 7b). Therefore, we interpret 490 Ma as the maximum depositional age of the siltstone; the other ages represent older detrital or captured zircons.

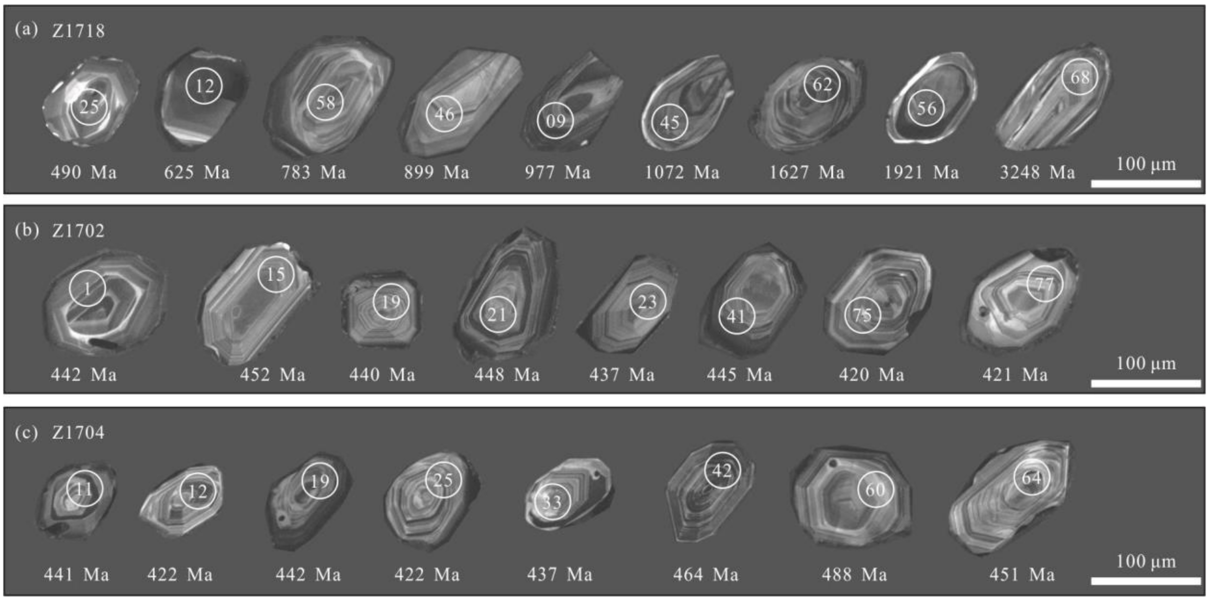

Figure 6. Cathodoluminescence (CL) images and test spots of representative zircons in this study

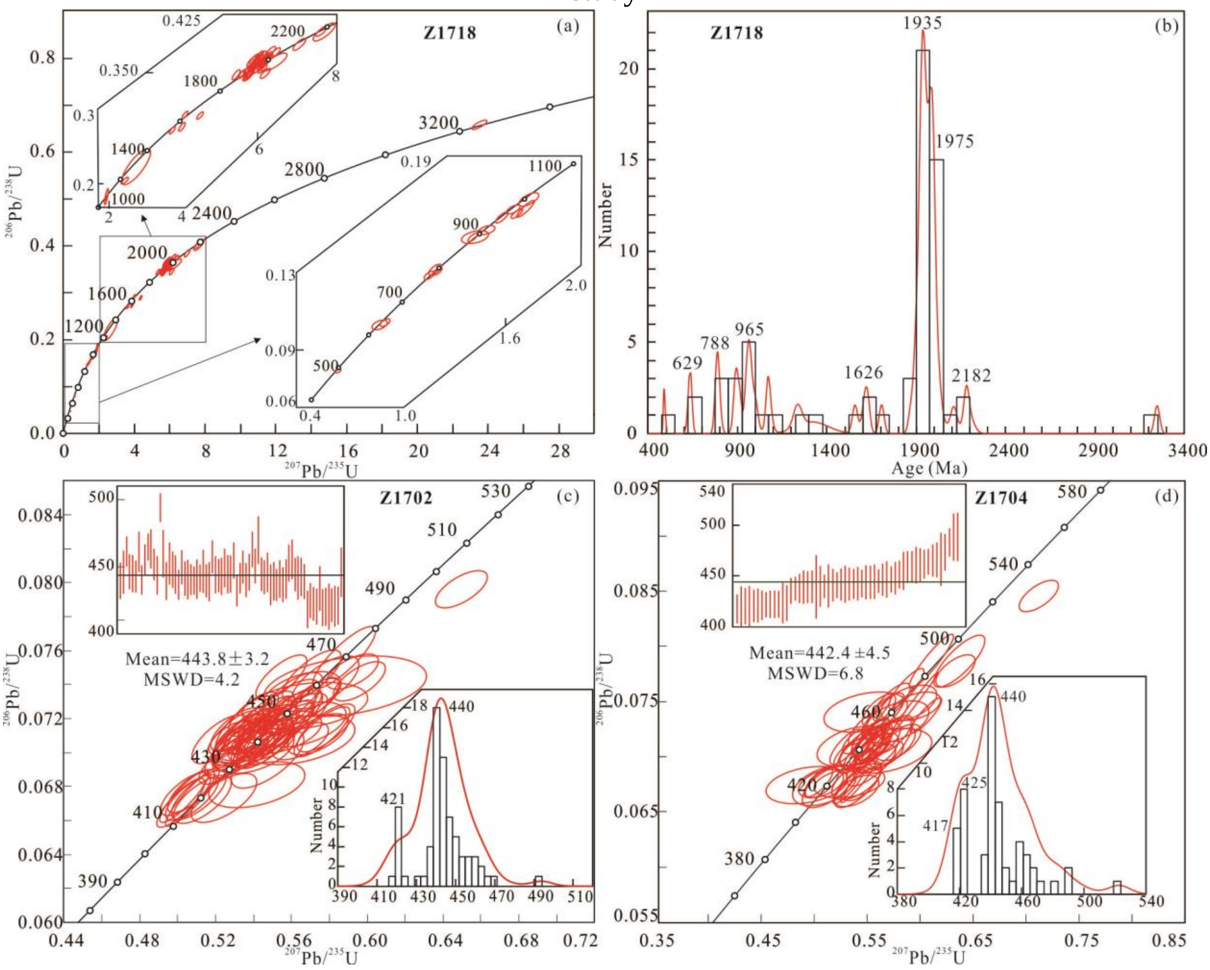

Figure 7. Zircon U-Pb Concordia diagrams and relative probability diagrams from the dated samples

Coarse sandstone (Sample Z1702): the majority of zircon grains separated from this sample are euhedral-subhedral. None of the zircon grains have a metamorphic rim, and they all have fine-scale oscillatory zoning (Figure 6b), indicating a magmatic origin (Th/U=0.41-1.32). A total of 80 zircon grains were analyzed, 74 of which passed the concordance filters (95%); they yield ages of 418- 493 Ma (Mean=443.8±3.2 Ma). The major peak centered at ca. 421 Ma to 440 Ma (Figure 7c). The zircon with a U-Pb age of 493 Ma is the oldest grain taken from this sample. The youngest age population of 419 Ma is interpreted as the maximum depositional age of the coarse sandstone.

Fine sandstone (Sample Z1704): the zircon grains in this sample display oscillatory zonation, and most of them are euhedral-subhedral without any metamorphic rim (Figure 6c). The Th/U ratios range from 0.44-1.60, indicting a magmatic origin. In total, 80 zircon grains were analyzed, of which 56 passed the concordance filters (95%). U-Pb dating indicates that the major age population lies in the range of 417-488 Ma, with three age peaks centered at ca. 417 Ma, 422 Ma and 438 Ma. Except for the one zircon grain age of 523 Ma, others have a mean age of 442.4±4.5 Ma (Figure 7d). The youngest age of 417 Ma is interpreted as the maximum depositional age of the fine sandstone. In addition, a single zircon grain with a U-Pb age of 1220 Ma may represent older detrital or captured zircons.

6 Discussion

6.1 Ages of the formations

Although the age data for the zircon grains from the Ayadeng formation is complicated, the estimate of 490 Ma could represent its maximum depositional age. However, the fossil evidence indicates that the formation dates back to the Ordovician, and so we might conclude that the Ayadeng formation belongs to an Ordovician layer rather than being a formation of the Bayan Obo group. Besides, the degree of metamorphism and deformation in the Ayadeng formation is lower than that of the Bayan Obo group (Zhang et al., 2004). The main metamorphic geology in the Bayan Obo group is low-grade greenschist, whereas the rocks in the Ayadeng formation only underwent slight metamorphism; this too suggests that the age of the Ayadeng formation is younger than that of the Bayan Obo group. The age of the fossils in the Xuniwusu and Xibiehe formations appear consistent with the U-Pb data. The maximum depositional age of the Xuniwusu formation is 440 Ma, while the age of the Xibiehe formation is 417-419 Ma; this lends support to the field observation that the Xibiehe formation unconformably covers over the Xuniwusu formation. Besides, the fossil corals also indicate that the Xuniwusu and Xibiehe strata formed in a warm shallow water environment with steady water activities.

6.2 Provenance and affinity of the early Paleozoic formation

The composition of the zircon grains from the Ayadeng formation is complicated, and this is particularly the case with grains occurring in the NCB, such as Bayan Obo. In this study, it is found that grains in the Ayadeng formation have an age range of 490-3247 Ma, with age peaks at 788 Ma, 894 Ma, 965Ma, and 1935 Ma, but no peaks at ca. 2500 Ma.

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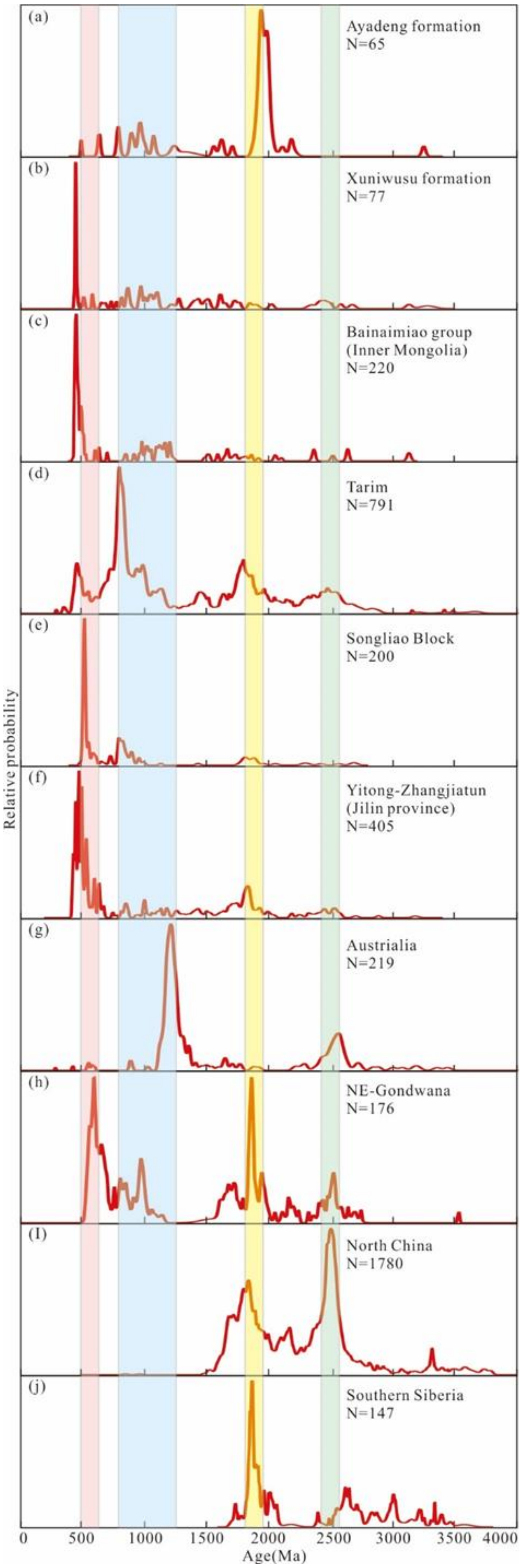

(a)
Ayadeng formation
N=65
(b)
Xuniwusu formation
N=77
(c)
Bainaimiao group
(Inner Mongolia)
N=220
(d)
Tarim
N=791
(e)
Songliao Block
N=200
(f)
Yitong-Zhangjiatun
(Jilin province)
N=405
(g)
Austrialia
N=219
(h)
NE-Gondwana
N=176
(I)
North China
N=1780
(j)
Southern Siberia
N=147
Relative probability
0 500 1000 1500 2000 2500 3000 3500 4000
Age(Ma)

Figure 8. Relative probability diagrams of U-Pb detrital zircon age distributions for comparing age-equivalent sedimentary samples from different blocks. (Date from: this study for Ayadeng Formation; Zhang et al. (2016) for Xuniwusu Formation; Zhang et al. (2014) for Bainaimiao Group; Dong et al. (2016), Rojas-Agramonte et al. (2011) for Tarim; Zhou et al. (2012) for Songliao Block; Wang et al. (2016), Zhou H. et al. (2018) for Yitong-Zhangjiatun area; Veevers et al. (2005) for Australia; Rojas-Agramonte et al. (2011) for NE Gondwana, North China Block and Southern Siberia)

There are many blocks and terranes alongside the CAOB, so it is necessary to compare and contrast the probability plots for North China Block (NCB), Siberia Carton (SC), Tarim (TA), Bainaimiao Arc Belt (BAB), Songliao Block (SB), Australia, NE Gondwana, and some U-Pb data from the Yitong-Zhangjiatun area (in the southern part of Jilin province) in order to determine their affinity and potential provenance (Figure 8). As the figure shows, although study area locations are geographically close to the NCB and SC, the composition of zircon grains from these places is considerably different from that of the late Mesoproterozoic-Neoproterozoic (720-1250 Ma) zircons. But they are very similar to the other microcontinents and terranes which are regarded as a part of North-East Gondwana (Li et al., 2017; Zhao et al., 2018). So, the zircon age of 778-1235 Ma in this study may represent the Grenville orogeny in Gondwana, and the age ranges of 490-636 Ma and 1320-3247 Ma may represent the Pan-African orogeny and Precambrian basement, respectively (Rojas-Agramonte et al., 2011; Zhou et al., 2017). Overall, the Ayadeng formation shares the closest similarity with Tarim and NE Gondwana, and it is also related to the Bainaimaio group pre-dating the Silurian (Zhang et al., 2014). According to existing geology maps, there have been few previously published reports on the Cambrian-Ordovician sedimentary strata in this study area and adjacent area. It may be speculated that the Ayadeng formation could be a source for the later meta-sedimentary strata in the BAB, or it might originally have been one part of the BAB. The thrust fault provides evidence of this: Zhou Z. G. et al (2018) estimated that a southward thrust appeared between the BAB and NCB during 450-410 Ma with a nappe distance longer than 19 km. Thus, the Ayadeng formation was most likely an original stratum in the BAB, which was then destroyed and transported in later tectonic activities.

Fossils in the Ayadeng formation can also provide supplementary clues. However, many of the *Ecculiomphalus* fossils identified in this study are damaged, and their species cannot be determined easily. In the *Ecculiomphalus kushanensis* (mainly occur in Liaoning and Hebei province, China) fossils the last spiral is wider, and a relatively obvious spiral edge can be observed on the abdomen (TIGMR, 1985). It should be noted that their spin ratios are dissimilar. These are similar to the *Ecculiomphalus sinensis* (mainly occur in Hubei and Guizhou province, China) fossils as they all have a spiral edge (HIGS, et al., 1977); however, we did not find a gap on the external lip, and there was a space within each spiral. They are more akin to *Ecculiomphalus kepintaghensis* (mainly occur in Xinjiang province, China) as they all have a spiral edge and contain spiral space (RGSBXGB et al., 1981). So, we consider that it may be a subspecies of *Ecculiomphalus kepintaghensis*. In addition, *Pararaphistoma qualteriatum* fossils were found mainly in Keping (Xinjiang province, China) and subspecies thereof were found in Keping and Benxi (Liaoning province, China) (Yü et al., 1963); according to the Paleobiology Datebase, such fossils can also be found in Australia, the Baltic region and Serbia. *Maclurites zhuozishanensis* and *Maclurites tofangoensis* fossils were found in Erdos (Inner Mongolia, China) and Liaoning respectively (BGIM & IGSNC, 1976). *Manchuroceras* sp. fossils were found mainly in North China and Northeast China (Zhu and Li, 2000), and also been found in South China, Korea and Australia (TIGMR, 1985). Overall, the fossils in the Ayadeng formation share an affinity with those in Tarim and North China, especially the *Ecculiomphalus* and *Pararaphistoma*, which indicate that the BAB is close to Tarim and NCB in the Ordovician.

We researched the occurrence of fossil findings of these four genera throughout the world in order to analyze their affinity (Figure 9). Discoveries of these fossils are confined mainly to Laurentia, the Baltic region and North China; they are considered to belong to independent blocks separate from Gondwana, and findings have been reported in South China, Australia, Songliao and Tarim. Researchers have suggested that the Tarim drifted off from northern Gondwana during the late Neoproterozoic to early Cambrian (Rojas-Agramonte et al., 2011; Li et al., 2008). According to paleomagnetism and paleontology evidence, all these blocks were located in low-middle latitudes and linked by an open ocean (Wang and Chen, 1999; Wright et al., 2013). Since the fossils in the Ayadeng formation share a closer affinity with those in Tarim in North China, and combining the composition of zircon grains ages, we speculate that it went through a process of shifting away from a location near Tarim or NE Gondwana to North China.

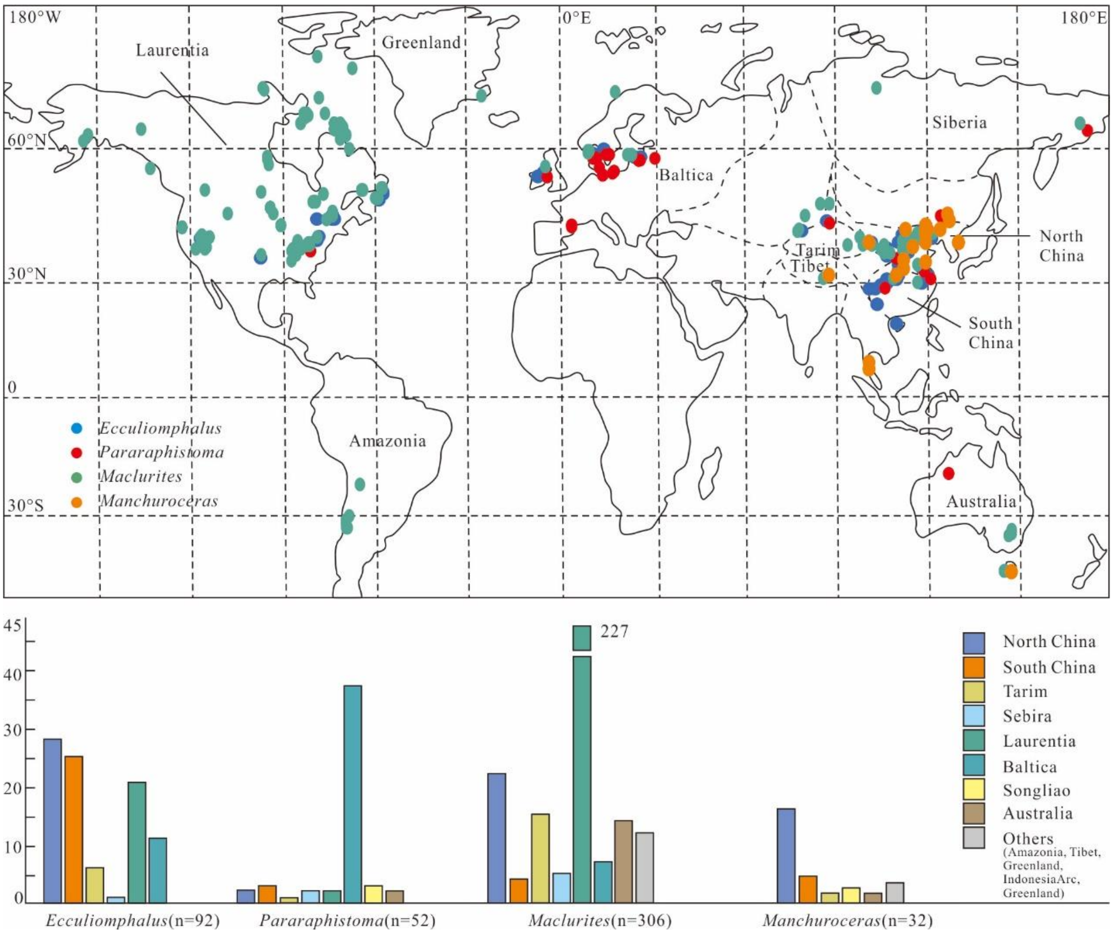

Figure 9. Fossil distribution map (Data download from the Paleobiology Datebase (https://www.paleobiodb.org/) on 11 November 2019, using the genus name: *Ecculiomphalus*,

Pararaphistoma, *Maclurites* and *Manchuroceras*)

The Xuniwusu formation has been researched only in recent years, and there are relatively few studies into the composition of zircon grains in the formation. For sample TM-11, a meta-sandstone sample from the Xuniwusu formation (Zhang et al., 2016), the probability density plots are similar to those in the Ayadeng formation, especially in samples dating to before ca. 440 Ma (Figure 8). Zircons grains whose ages occur in the 600-1250 Ma may have been transported from Ayadeng to Xuniwusu after 440 Ma (the maximum depositional age of the Xuniwusu formation, also consistent with the thrust fault). In general, the age of the Xuniwusu formation is little younger than that of the Bainaimiao group (Zhang et al., 2014; Zhang et al., 2019), which is in accordance with field surveying data. The zircon grains in the Xibiehe formation are characterized by an obvious angular shape and lack of rounding. Their ages are also fairly centered, which indicates a process of rapid proximal sediment accumulation. The composition of zircon grains in the Xibiehe formation is relatively simple, with an age peak that is compatible with their provenance. Many igneous rocks in adjacent area dating from the same period might constitute its source (Figure 2). In addition, the paleontological species in the Xuniwusu and Xibiehe formations are very similar: *Favosites*, *Heliolites* and *Mesofavosites* were all found in these two strata. According to the public paleobiology database, these same fossil corals mainly appear in Laurentia, Siberia, Australia, Mongolia, South China and Tarim, but are rare in North China. This might suggest that the topography in North China underwent significant changes during the Ordovician and Silurian periods, as evidenced by the change of sedimentary facies: the seawater almost completely retreated from the north margin of the NCB (Chen et al., 2015), and these topography changes might be cause by the collision between BAB and NCB.

6.3 Tectonic implications

In recent years there have been studies about the BAB which have been concentrated mainly on igneous rocks, detrital zircon and geochemistry. Xiao, et al. (2003) regarded that the BAB extends from Bayan Obo in the west to Chifeng in the east. Zhang, et al. (2014) extended the range of BAB further east to Changchun, which is characterized by similar features in terms of geochemistry and zircon composition. Wang, et al. (2016) and Zhou, H. et al. (2018) also found early Paleozoic groups in east Jilin province, which share similar features with the BAB in terms of petrographic composition, age and isotopes. So, we consider that the BAB extends along the whole north side of the NCB and has a comparatively uniform material composition. Some scholars have regarded the BAB as an ocean island arc like the Japanese islands (Tang, 1990; Hu et al., 1990), but more recent research studies have shown that an intra-oceanic arc is unlikely to be formed via oceanic-oceanic subduction, and many previous intra-oceanic arcs are therefore considered to be fragments from a continental margin (Wu et al., 2019). In relative terms, we tend to regard the BAB as an extra fragment that has its own Precambrian basement, which is different from the NCB. This suggestion is not only supported by the occurrence of late Neoproterozoic to early Cambrian zircons and fossils, but also indicated by later volcanic rocks. The Permian volcanic rocks in the BAB and NCB have different ε_{Hf} (*t*), and the zircon composition of the andesite in BAB is also more complex (Wang et al., 2019). Therefore, a rift might have separated the BAB from the Tarim or NE Gondwana, and the BAB might have then drifted to the NCB before becoming involved in the early Paleozoic tectonic evolution of the CAOB.

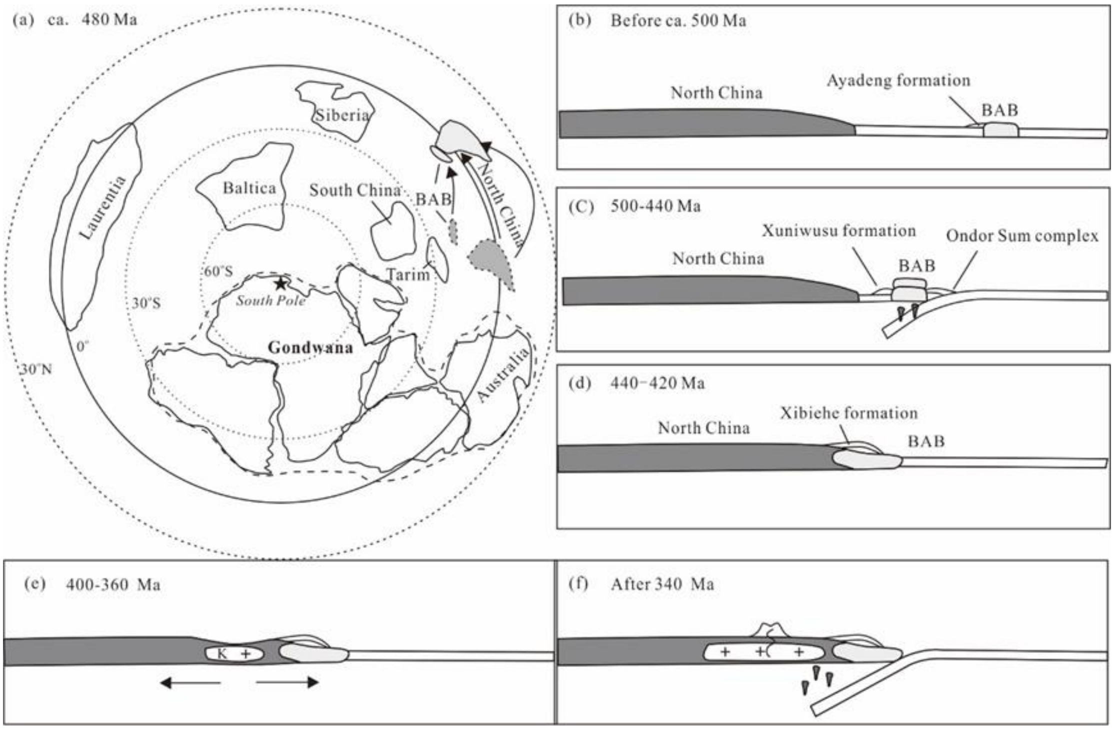

Figure 10. (a) Reconstruction of southern hemisphere showing hypothetical paleo-position of BAB (modified after Cocks and Torsvik, 2002). (b) Tectonic evolution diagrams of the Bainaimiao Arc Belt. (modified after Ma et al.,2019)

Paleomagnetic and paleontological techniques are the most common methods used to reconstruct the paleo-plates in geological history. In recent years, researchers have conducted a number of studies to determine plate locations throughout the Paleozoic era; however, the exact locations of Tarim and the NCB remain unresolved. Zhao, et al. (2018) and Li, et al. (2001) placed Tarim in a higher paleolatitude and away from North China and South China during 500-460Ma; however, other scholars have suggested that Tarim was closer to South China and Australia in NE Gondwana (Cork and Torsvik, 2002, Wang et al., 2016; Fortey et al., 2003). Having analyzed a substantial number of fossils (Wang and Chen, 1999), we prefer the latter theory. Another unresolved issue is the drifting trajectory of North China. Many researchers have considered that North China was near South China and Australia during the early Paleozoic (Li et al., 2008). Wang and Chen (1999) suggested the North China moved from south to north, from a low paleolatitude to a middle-high paleolatitude in the northern hemisphere during the Ordovician, as evidence by an increase of cold-water type fauna. Zhu, et al. (1998) suggested the North China moved north from low-middle paleolatitude in southern hemisphere. Nie, et al. (2015) suggested that North China might have been approaching a low paleolatitude area. More evidence is needed before these questions can be conclusively answered; however, on the basis of the results presented above, we propose the following scenario (Figure 10a): prior to ca 500 Ma, the BAB had been separated from Tarim or NE Gondwana, and it was located near South China and North China; it then drifted towards and became attached to North China in a low-middle paleolatitude during the early Silurian.

Combining our data on the petrographic composition in samples from the BAB and

NCB with those in previous research results, we can speculate on the evolution of the BAB during the Paleozoic era. Before ca. 500 Ma (Figure 10b), the BAB had been divided from Tarim or NE Gondwana; the BAB then drifted to the NCB, but without any magma activity occurring. At this point, deposits comprised mainly carbonate sediments. After 500 Ma (Figure 10c), the BAB started attaching to the NCB, and substantial volcanic and pyroclastic (Bainaimiao group) and intrusive rocks appeared in the BAB. As these rocks only appear in the BAB, Zhang, et al. (2014) have suggested that during this period the South Bainaimaio oceanic plate subducted northward beneath the BAB. However, according to the geochemistry data in this area, the K_2O ratio increases from north to south (Figure 11), from old to young (Chen et al., 2020), which may indicate that the younger pluton in the south was far away from the trench. In addition, the ophiolitic melanges in the Ondor Sum accretionary complex are widely regarded as the result of a southward subduction (Liu et al., 2003; Xu et al., 2016). Therefore, a southward subduction may have contributed to this phenomenon. Meanwhile, the Xuniwusu formation (440 Ma), which consists of a series of marine pyroclastic strata, formed along the BAB. From ca. 420 Ma (Figure 10d), the BAB collided with the NCB; during this period, molasse sediments (Xibiehe formation) and some ophiolitic melanges formed in Bayan Obo and Damaoqi (Zhang et al., 2014). Considering the differences between the crystallization ages of detrital zircons and the depositional ages of these formations, we can also conjecture the tectonic settings during the time of their formation (Figure 12): the Ayadeng formation may have formed in an extensional setting, while the Xuniwusu formation and Xibiehe formation mainly formed in a collisional setting. Until that point, the BAB and the NCB may have been linked together, but we cannot confirm whether the paleo-Asian ocean had disappeared by then. Since the latest paleomagnetism data reveal that the NCB was located at ~22.3°N and Siberia was at ~45°-65°N during the Carboniferous period, there is no significant latitudinal difference between the CAOB blocks until the Late Permian to Early Triassic (Zhang et al., 2018). So, we prefer the theory arguing that the paleo-Asian ocean still existed in the early Paleozoic era. In ca. 400-360 Ma (Figure 10e), the NCB might have become involved in an extensional event, according to the alkali granite (Wang, 2014). After ca. 340 Ma (Figure 10f), increased magma activities occurred in the BAB and along the northern side of the NCB, which might represent the beginning of the southward subduction of the paleo-Asian ocean, a process which might have lasted until the early Triassic (Zhang et al., 2010; Guan et al., 2018).

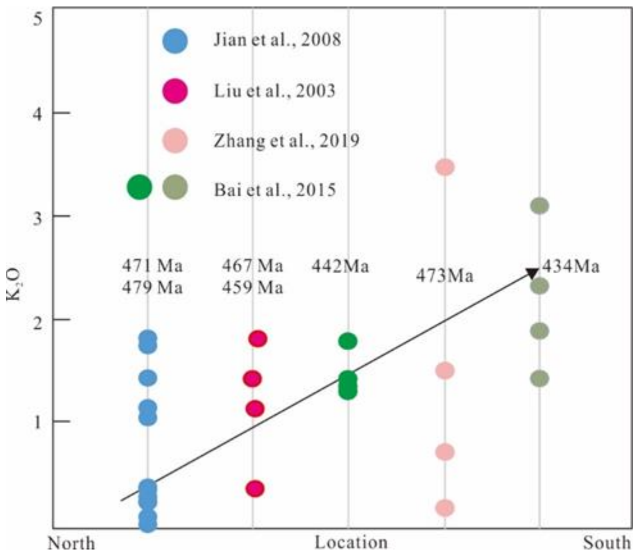

Figure 11. Location-dependent variations K2O contents

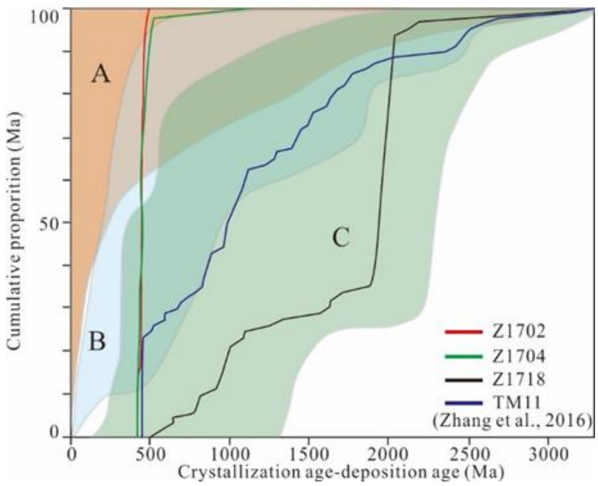

Figure 12. Variation of the differences between the crystallization ages of detrital zircons and the depositional age of the sedimentary sequence, plotted as cumulative proportion cures. A, convergent setting; B, collisional setting; C, extensional setting (After Cawood et al., 2012 and Xiong et al., 2019)

7. Conclusions

1. Zircon U-Pb geochronological and paleontological data of samples taken from the newly identified early Paleozoic stratum in the Ayadeng formation indicate that the formation is different from the Bayan Obo group and might be an original stratum thrust from the BAB. Its zircon composition is different from that of the NCB, whereas the appearance of the zircons and their age (ca. 600-1250 Ma), are similar to that of zircon grains in Tarim and NE Gondwana. Considering the similarity of fossils between Ayadeng and Tarim, we suggest that the BAB is an exotic fragment, which separated from Tarim or NE Gondwana in the early Paleozoic.

2. The zircon composition in the Xuniwusu formation share an inheritance with that in the Ayadeng formation. The maximum depositional age suggest that the BAB had originally

been attached to the NCB ca. 440Ma; the zircon composition of Xibiehe formation is uniform and concentrated, indicating a process of rapid proximal sediment accumulation. Its maximum depositional age, ca. 420 Ma, represents the collision between the BAB and NCB. The coral fossils reveal that these series of procedures happened in a warm shallow water environment. In the early Paleozoic, there may have occurred a collision between an arc and a continental block.

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