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Jurassic integrative stratigraphy and timescale of China

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Abstract The Jurassic stratigraphy in China is dominated by continental sediments. Marine facies and marine-terrigenous facies sediment have developed locally in the Qinghai-Tibet area, southern South China, and northeast China. The division of terrestrial Jurassic strata has been argued, and the conclusions of biostratigraphy and isotope chronology have been inconsistent. During the Jurassic period, the North China Plate, South China Plate, and Tarim Plate were spliced and formed the prototype of ancient China. The Yanshan Movement has had a profound influence on the eastern and northern regions of China and has formed an important regional unconformity. The Triassic-Jurassic boundary (201.3 Ma) is located roughly between the Haojiagou Formation and the Badaowan Formation in the Junggar Basin, and between the Xujiahe Formation and the Ziliujing Formation in the Sichuan Basin. The early Early Jurassic sediments generally were lacking in the eastern and central regions north of the ancient Dabie Mountains, suggesting that a clear uplift occurred in the eastern part of China during the Late Triassic period when it formed vast mountains and plateaus. A series of molasse-volcanic rock-coal strata developed in the northern margin of North China Craton in the Early Jurassic and are found in the Xingshikou Formation, Nandailing Formation, and Yaopo Formation in the West Beijing Basin. The geological age and markers of the boundary between the Yongfeng Stage and Liuhuanggou Stage are unclear. About 170 Ma ago, the Yanshan Movement began to affect China. The structural system of China changed from the near east-west Tethys or the Ancient Asia Ocean tectonic domain to the north-north-east Pacific tectonic domain since 170–135 Ma. A set of syngenetic conglomerate at the bottom of the Haifanggou or Longmen Fms. represented another set of molasse-volcanic rock-coal strata formed in the Yanliao region during the Middle Jurassic Yanshan Movement (Curtain A1). The bottom of the conglomerate is approximately equivalent to the boundary of the Shihezi Stage and Liuhuanggou Stage. The bottom of the Manas Stage creates a regional unconformity in northern China (about 161 Ma, Volcanic Curtain of the Yanshan Movement, Curtain A2). The Jurassic Yanshan Movement is likely related to the southward subduction of the Siberian Plate to the closure of the Mongolia-Okhotsk Ocean. A large-scale volcanic activity occurred in the Tiaojishan period around 161–153 Ma. Note that 153 Ma is the age of the bottom Tuchengzi Formation, and the bottom boundary of the Fifth Stage of the Jurassic terrestrial stage in China should have occurred earlier than this. This activity was marked by a warming event at the top of the Toutunhe Formation, and the change in the biological assembly is estimated to be 155 Ma. The terrestrial Jurassic-Cretaceous boundary (ca. 145.0 Ma) in the Yanliao region should be located in the upper part of Member 1 of the Tuchengzi Formation, the Ordos Basin in the upper part of the Anding Formation, the Junggar Basin in the upper part of the Qigu Formation, and the Sichuan Basin in the upper part of the Suining Formation The general characteristics of terrestrial Jurassic of China changed from the warm and humid coal-forming environment of the Early-Middle Jurassic to the hot, dry, red layers in the Late Jurassic. With the origin and development of the *Coniopteris-Phoenicopsis* flora, the Yanliao biota was developed and spread widely in the area north of the ancient Kunlun Mountains, ancient Qinling Mountains, and ancient Dabie Mountain ranges in the Middle Jurassic, and reached its great prosperity in the Early Late Jurassic and gradually declined and disappeared and moved southward with the arrival of a dry and hot climate.

Keywords Continental Jurassic, Biostratigraphy, Isotope chronology, Age frame, Yanshan Movement, Yanliao biota

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1. Introduction

After the Triassic Indosinian Movement, the collision between the Sino-Korean Plate and the South China Plate with the Tarim Block formed the prototype of China's ancient mainland (Figure 1). The major areas in China ended the drift, collision, and splicing of small plates and entered the intracontinental structural deformation stage in the Jurassic period.

The Jurassic stratigraphy of China is dominated by continental deposits, and it is widely developed on the ancient North China Platform and Yangtze Platform. It also includes a number of large inland basins, including the Ordos Basin, the Qaidam Basin, the Tarim Basin, the Junggar Basin, the Sichuan Basin, and the Dianzhong Basin. In the Qinghai-Tibet region, southern South China, and eastern Heilongjiang, the marine or marine-terrigenous strata are developed (Figure 1).

China's terrestrial Jurassic system has developed important coal-bearing strata and metal and nonmetallic minerals, which have important economic implications (Deng et al., 2007). Coal resources, in particular, account for nearly two-thirds of China's total reserves (Wang et al., 1994). Jurassic terrestrial strata have yielded several important exceptional fossil preservations, characterized by the Yanliao biota, and have provided important data for Mesozoic evolution (Huang, 2016). Influenced by the Yanshan Movement in the Middle Jurassic, many north-north-east intermountain basins have developed. Therefore, the nature of the Yanshan Movement is considered by some researchers to be the east-west transition of the Tethys tectonic domain or to be the Ancient Asian Ocean tectonic domain change to the north-north-eastern Pacific Ocean tectonic domain (Zhao, 1994). The lithology of these basins often varies, the fossils are sometimes difficult to compare, and reliable isotope ages generally are absent. Therefore, the stratigraphic correlation of Jurassic continental basins has always been different. One finding is concrete: the biostrata derived from different fossils have inconsistent conclusions and major differences exist in the ages of isotopic chronology and biostratigraphy (Wang et al., 2013; Huang, 2015). These problems are important because the distribution and evolution of terrestrial organisms have regional characteristics, and it is difficult to compare these characteristics with the standardized strata of European marine deposits. The technical methods of the isotope chronology are inadequate and the results are not sufficiently accurate. Systematic isotope chronological data outside the Yanliao region generally are absent.

The study of Mesozoic biostratigraphy in China started relatively early. For example, Ye (1920) first established the regional stratigraphic framework of China in his book *Geological History of Xishan*, *Beijing*, which is used today. Grabau erected the Jehol system in 1923 and the Jehol biota in 1928, which was attribute to the Early Cretaceous (Grabau, 1923, 1928). The issue of the Jehol biota was controversial in the second half of the last century. With the development of the research of the Mesozoic continental strata in China, in particular, the great development of precise isotope chronology, many researchers generally accept that the absolute age of the *Confuciusornis*-gathering layer in the Jehol biota is about 125 Ma. In contrast, according to recent opinions, the Chinese terrestrial Cretaceous age is younger, which presents a challenge to the study of Jurassic biostratigraphy. In addition, the international stratigraphic chart has undergone a major shift in the definition of the Jurassic-Cretaceous boundary, from 135 Ma (Remane, 2000) to 145 Ma (Cohen et al., 2013), resulting in confusion pertaining to the Late Jurassic biostratigraphy.

This paper analyzes and compares the Jurassic continental strata in China on the basis of the regional tectonic movement and biostratigraphy, with isotope geochronology providing the quantitative basis. This study provides more comprehensive comparisons and time frames for Jurassic strata in China. The work of the Jurassic magnetic stratigraphy and chemical stratigraphy is not yet systematic, and thus it is not introduced in the present paper.

2. Brief history of Chinese Jurassic studies

The Jurassic system is divided into 3 series and 11 stages. From the bottom to the top, the Jurassic system consists of the Lower Jurassic Hettangian, Sinemurian, Pliensbachian, and Toarcian; the Middle Jurassic Aalenian, Bajocian, Bathonian, and Callovian; and the Upper Jurassic Oxfordian, Kimmeridgian, and Tithonian. The determination of the bottom boundaries of the Jurassic stages is based on the first occurrence of a specific ammonite belt. The International Stratigraphic Commission confirmed the Global Boundary Stratotype Section and Point (GSSP) of the lower seven stages. The boundary of the Triassic-Jurassic system is 201.3 ±0.2 Ma, and the boundary of the Jurassic-Cretaceous system is approximately 145 Ma (Fan et al., 2016). The Ar-Ar age of the bottom basalts of the first Cretaceous stage Berriasian of the Shatsky Rise in the northwest Pacific is 144.6±0.8 Ma, which is the most significant reference to the Jurassic-Cretaceous boundary age (Mahoney et al., 2005).

Jurassic studies in China began in the late 19th century. Wong (1927) proposed the concept of the Yanshan Movement formally according to the Jurassic geological phenomenon in the Jingxi Basin. It is still one of the most popular research fields in Chinese geology. Senior geologists conducted a series of pioneering studies on the Jurassic system in China, such as Wang Zhuquan's research on the Jurassic coal fields in the north, Li Siguang, Huang Jiqing, Li Chunyu, Yang Zhongjian, and Si Xingjian's study of the

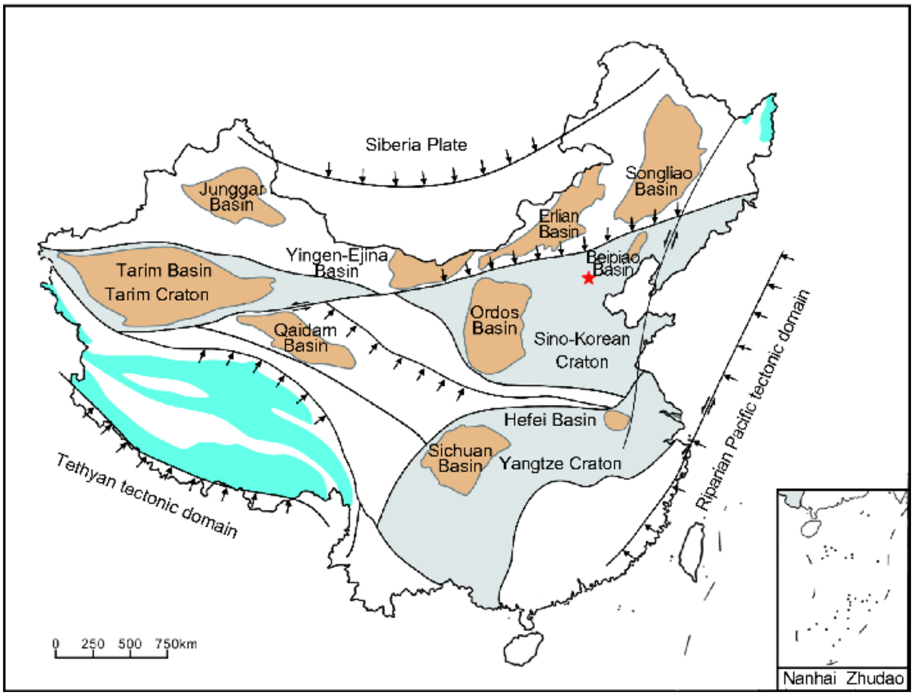

Figure 1 The general characters of the Jurassic deposition in China. Brown color represents the major terrestrial basins and the blue color represents the marine strata.

western Hubei Province and the Sichuan Basin (Wang, 1985b) before 1949. After the liberation, Chinese seniors systematically studied the Jurassic strata and completed some influential reviews, such as "The Jurassic and Cretaceous of China" (Gu, 1962), "Mesozoic Terrestrial Strata in China" (Si and Zhou, 1962), "The Jurassic of China" (Wang, 1985b), and others, including most notably the "The Jurassic System of North China" series of monographs, conducted in China's major Jurassic areas.

In recent years, the Jurassic research of China has achieved important developments. For example, the successful conclusion of the Eighth International Jurassic Conference in Sichuan, and the implementation of a series of Jurassic International Geological Comparison Programs (IGCP) have provided solutions to some key scientific issues. In addition, the study of the exceptional biotas of Jurassic stratigraphy in China has become the key to understanding the evolution of the terrestrial ecosystem in the Middle Mesozoic.

3. Continental Jurassic stratigraphic framework of China

The National Stratigraphic Commission made a fundamental suggestion regarding the construction of major definite strata in China based on the Haojiagou Section and the Honggou Section of the Junggar Basin as a candidate section of the Lower-Middle Jurassic. This section was divided into four stages from the bottom to the top: the lower Jurassic Badaowan Stage, Sangonghe Stage, the Middle Jurassic Xishanyao Stage, and Toutunhe Stage. On the basis of the stratigraphy of Yanliao region, the Upper Jurassic Tuchengzi Stage was established from the Jinlingsi-Yangshan Basin in the western part of Liaoning Province, and the Upper Jurassic Dabeigou Stage was established from the Luanping Basin in the northern part of Hebei Province (Jiang et al., 2008a, 2008b, 2008c, 2008d; Wang and Ji, 2008). According to the current International Stratigraphic Chart and a large amount of geological work in recent years, it is known that the Dabeigou Stage belongs to the Lower Cretaceous; therefore, it is not included in the scope of the present study. According to the decision of the editorial committee of the "Chinese Stratigraphic Table" of the Chinese Stratigraphy Committee (2014), five stages have been established for Chinese Jurassic strata as follows: the Lower Jurassic Yongfeng Stage (corresponds to the Badaowan Formation, the former Badaowan Stage), the Liuhuanggou Stage (corresponds to the Sangonghe Formation, the former Sangonghe Stage), the Middle Jurassic Shihezi Stage (corresponds to the Xishanyao Formation, the former Xishanyao Stage), and the Manas Stage (corresponds to the Toutunhe Formation, the former Toutunhe Stage). These names were changed because the name of the stage and the formation cannot be synonymous. The Upper Jurassic did not build stages, but it corresponds to the Tuchengzi Formation in northern China and the Suining Formation and Penglaizhen Formation in southern China (the former Tuchengzi Stage).

The Jurassic strata in the Junggar Basin of Xinjiang are well developed, and the tectonic movements are strongly influenced by the eastern and western margins of the basin. The strata on the southern margin basically were continuous, indicating that they are closer to the sedimentary center and are less affected by tectonic movements. At the end of the last century, the Jurassic system of the Junggar Basin already had divided into three series and six Fms. (Lu, 1995). The National Stratigraphic Commission conducted a study on the Lower-Middle Jurassic chronostratigraphic candidates of the Haojiagou Section in Urumqi City and the Honggou Section in Shawan County (Jiang et al., 2008a, 2008b, 2008c, 2008d).

This paper indicates that the Triassic-Jurassic boundary in the Junggar Basin is located roughly between the Haojiagou and the Badaowan Fms., and the Jurassic-Cretaceous boundary is located in the upper part of the Qigu Formation The Jurassic system in the Haojiagou and Honggou sections is divided into five Fms. from the bottom to the top, followed by the Badaowan Formation, the Sangonghe Formation, the Xishanyao Formation, the Toutunhe Formation, and the Qigu Formation At the Badaowan Formation, at the standard section of Haojiagou, there are conglomerate and pebbly coarse sandstones with carbonaceous mudstone at the bottom that conform with the underlying sandstone and mudstone in the Upper Triassic Haojiagou Formation This section is divided into the lower coal-bearing member, the middle mudstone member, and the upper coal-bearing member. The Sangonghe Formation consists of four to five massive sets of thick yellowish green sandstone with conglomerate. It contains siltstone, mudstone, carbonaceous shale, and coal line at the standard section of Fukang County. The Xishanyao Formation was established in the Xishan Coal Mine of Urumqi City. It is the main coal-bearing strata in Xinjiang and consists of sandstone, siltstone, and pebbly sandstone, and interposed carbonaceous mudstone, coal, and siderite. The Toutunhe Formation was established in the Toutunhe Section of southwest Urumqi. It features a set of variegated glutenite, sandstone, and mudstone alternating strata, with mudstone, carbonaceous mudstone, or coal in the middle section. The Qigu Formation, which is overlying the variegated layer of the Toutunhe Formation, features a set of red layers underlying the glutenite of the Kalazha Formation, with a few layers of tuff (Deng et al., 2010).

3.1 The Yongfeng Stage

The Yongfeng Stage corresponds to the age of the Badaowan Formation The bottom of the Badaowan Formation is very close to the Triassic-Jurassic boundary (Deng et al., 2003; Lu and Deng, 2005; Sha et al., 2011, 2015). The Yongfeng Stage corresponds at least to the age of the Hettangian and Sinemurian stages (Deng et al., 2003; Sha et al., 2016) and its upper section also may include part of the Pliensbachian. The strata of the Yongfong Stage is not found in most areas of China, but it did develop in the Junggar Basin, the Qaidam Basin, and the Sichuan Basin. The palaeontological assemblage of the standard section of the Badaowan Formation follows (Jiang et al., 2008d; Deng et al., 2010). The bivalves and conchostracans are distributed primarily in the middle and upper sections. The bivalves *Ferganoconcha* and *Waagenoperna* are relatively abundant, with some *Kija*, *Margaritifera*, *Unio*, *Cuneopsis*, and *Sibireconcha*. The conchostracans belong to the *Palaeolimnadia baitianbaensis* fauna. Plants are divided into two assemblages: *Todites princeps*, an important form of the Early Jurassic, which characterizes the lower assemblage along with other prosperous Jurassic groups, such as *Ginkgoites*, *Baiera*, *Sphenobaiera*, and *Czekanowskia* (no *Coniopteris*). Such a feature is representative of the early plant assemblage of the Early Jurassic. The upper assemblage is characterized by the flourishing of *Coniopteris* and *Cladophlebis* and is representative of the features of the middle Early Jurassic. The pollen and spores have shown an assemblage of *Osmundacidites*-*Cerebropollenites*-*Protoconiferus* (Deng et al., 2003).

The volcanic rocks of the Yongfeng Stage are not developed, and few isotopic geochronological studies have been conducted. An Early Jurassic basalt developed near the Karamay City of the northwestern margin of the Junggar Basin and appeared as interbeds in the lower part of the Badaowan Formation This section was in contact with the roast sandstone at the bottom. The Ar-Ar age was 192.7±1.3 Ma at the upper part of the Sinemurian (Xu et al., 2008). Therefore, the upper part of the Badaowan Formation should have extended to the Pliensbachian.

3.2 The Liuhuanggou Stage

Due to the lack of reliable biostratigraphic data and isotope dating, it is difficult to accurately determine the boundary age of the Liuhuanggou and Yongfeng stages. The Liuhuanggou Stage corresponds to the Toarcian and the Aalenian, and probably also includes the Bajocian, and its lower section contains part of the Pliensbachian. The palaeontological assemblage of the standard section of the Badaowan Formation follows (Jiang et al., 2008c; Deng et al., 2010). For bivalve assemblages, including *Kija*, *Ferganoconcha*, *Margaritifera*, *Unio*, *Pseudocardinia*, and *Tutuella rotunda*, *Kija* increased, *Ferganoconcha* declined, and *Waagenoperna* disappeared. The conchostracans are mainly composed of *Palaeolimnadia*, including *P. grandis*, *P. chuanbeiensis*, and *P. baitianbaensis*. Plants dominated by ferns, sphenopsids, ginkgo, and *Coniopteris* were more common, such as *Coniopteris hymenophylloides*. *Equisetites* and various *Coniopteris* have been found in the upper section, and

Cladophlebis sp., *Coniopteris* sp., *Todites denticulatus*, *Desmiophyllum* sp., *Czekanowskia pumila*, *Gleichenites nitida*, *Phoenicopsis angustifolia*, and *Podozamites* sp. have been found in the lower section. The pollen and spores have shown a *Deltoidospora*-*Classopollis*-*Piceites* assemblage, which is similar to the assemblages of the Wudanggou Formation and Beipiao Formation The Liuhuanggou Stage is an important Jurassic coal-bearing strata in eastern China. For example, Beipiao Formation, Yaopo Formation, and Datong Formation all correspond to the age of the upper part of the Liuhuanggou Stage, which belonged to the early Middle Jurassic.

No reliable isotope age has been published in the Beipiao Formation of northwestern Liaoning and the Yaopo Formation of western Beijing. It generally is considered to belong to the late Early Jurassic period. Some researchers believe that the upper parts of the Beipiao Formation belong to the Middle Jurassic. Yang et al. (2006) believe that the youngest detrital zircon (145±2 Ma) in the Shangyaopo Formation represents its age, which is obviously incorrect, whereas the latest group with four zircons (174±2 Ma) may represent the true age of the Yaopo Formation The Xinglonggou Formation in western Liaoning Province and the Nandaling Formation in western Beijing are volcanic rocks and sometimes contain sedimentary rock interlayers. Their geological ages are controversial. There are four isotopic ages in Xinglonggou Formation: (1) about 202 Ma (Shao and Yang, 2011); (2) about 188–190 Ma (Chen and Chen, 1997); (3) about 177 Ma (Yang and Li, 2008); and (4) about 159 Ma (Gao et al., 2004). Note that 159 Ma is considered to be the age of felsophyre veins throughout the volcanic-sedimentary strata of Xinglonggou Formation (Shao and Yang, 2008), 202 Ma is the age of the end of the Triassic, and it is difficult to obtain the support of other evidence. The Nandaling Formation in western Beijing correlates to the Xinglonggou Formation in western Liaoning, and the former initially was used as a diabase intrusion in the Mentougou Series (Ye, 1920). The lower part of the Nandailing Formation is basalt, and the andesite and tuff interbeds developed in the upper part at some area. The analysis of zircon in basalt has yielded an age peak of 190 Ma, which is believed to be related to intracontinental tectonic-magmatic activities in the Early Jurassic, and 174±8 Ma represents the true age of the Nandailing Formation (Zhao et al., 2006). There is no difference between fossil plants in the upper andesite interlayers (i.e., Caijialing Formation) of the Nandaling and Yaopo Fms. in western Beijing (Chen et al., 1984). Some fossil plants found in the tuff interlayer of the Nandailing Formation at Shanggu Section, Chengde City, Hebei Province, have been assigned within the Early Jurassic (Sun et al., 1996). Some conchostracans, namely *Palaeolimnadia*, also were found, which is indicative of the Early Jurassic stratum (Mi et al., 1993). The basalts and andesites of the Nandaling Formation belong to the bimodal volcanic rocks, and their eruption times are close to each other (Wang et al., 1995). Therefore, 174±8 Ma represents the age of the Nandailing Formation, and 176.7±3.5 Ma represents the age of the Xinglonggou Formation In addition, some researchers have performed a zircon U-Pb dating on the volcanic rocks originally assigned to the Xinglonggou Formation and obtained the age of 173.4±3.1 Ma, which is considered to belong to the Haifanggou Formation (Ma, 2013). From the present analysis, this volcanic rock is still attributed to the Xinglonggou Formation.

The Xingshikou Formation of western Beijing normally has a thickness of no more than 80 meters and initially was considered to belong to the Jurassic. The fossil plants indicate an appearance of the Jurassic Mentougou flora (Yang, 1957; Chen et al., 1984), but some researchers believe those fossil plants denote the characteristics of the Late Triassic (Mi et al., 1984). The palaeoniscid fishes of the Xingshikou Formation resemble those of the Upper Triassic Yanchang Formation (Liu, 1988), but they are more similar to the *Daqingshaniscus* of the Middle Jurassic Zhaogou Formation The latter correlates to the Haifanggou Formation *Daqingshaniscus* was collected from the top of the Zhaogou Formation, which suggests a possible Late Jurassic age and is associated with the representative palaeoniscids of the Late Jurassic Linglongta biota (Huang, 2015). Therefore, from the evidence of these palaeoniscids, the Xingshikou Formation is more like the Early Jurassic than the Late Triassic. Yang et al. (2006) determined that the youngest detrital zircon is 205±1 Ma of the Xingshikou Formation in Beijing, which indicated that the age of the Xingshikou Formation may be later than the Triassic. These magmatic zircons are common recycled zircons in the Middle-Late Jurassic strata of the Yanliao region. They represent important magmatic activity and are consistent with the age of early granites in the Wangtufang complex rock in the Chengde area. This also represented a rapid uplift in the northern margin of North China in the Late Triassic-Early Jurassic (Liu et al., 2007; Liu J et al., 2012). Some researchers have determined the youngest detrital zircon age of 197±6 Ma in the Xingshikou Formation of the Xiabancheng Basin in Chengde, which also supports the Jurassic age of the Xingshikou Formation (Liu et al., 2007; Liu J et al., 2012). A set of clastic rock strata beneath the Xinglonggou Formation in western Liaoning (formerly known as the Shimengou Formation and the Kuntouboluo Formation) currently is referred to as the Upper Triassic or Upper Triassic-Lower Jurassic Yangcaogou Formation (Mi et al., 1993; Liaoning Bureau of Geology and Mineral Exploration and Development, 1997), but this strata requires further study.

An accurate understanding of the volcanic rocks of the Nandaling and Xinglonggou Fms. indicates they are located near the vicinity of the Early-Middle Jurassic boundary, and not near the early Early Jurassic strata. The underlying Xingshikou Formation also should be considered as middle-late Early Jurassic deposits. Therefore, early deposition of the early Early Jurassic was absent in the Yanliao region (Figure 2). The ages of the Yaopo and Beipiao Fms. are constrained by the age of volcanic rocks of the Nandaling and Xinglonggou Fms. On the basis of the analysis of the flora, some researchers believe that the Yaopo and Beipiao Fms. belong to the Middle Jurassic (Xu, 1979; Duan, 1989). This hypothesis is now supported by the underlying isotope age. These volcanic rocks erupted many times near the Early-Middle Jurassic boundary (174.1±1.0 Ma). The bottom of the Yaopo and Beipiao Fms. in some areas may be from the late Early Jurassic.

The Xingshikou Formation-Nandaling Formation-Yaopo Formation in the Jiangxi Basin; the ?Yangcaogou Formation-Xinglonggou Formation-Beipiao Formation in the Beipiao Basin; and the Yongdingzhuang Formation-Datong Formation in the northwestern Shaanxi Province all correspond closely to the Liuhuanggou Stage and all have a set of fluvial molasses at bottom. The relationship of these molasses to the bottom Sangonghe Formation is not yet clear. The age of the volcanic rocks still holds important significance for understanding the bottom boundary age of the Liuhuanggou Stage.

3.3 The Shihezi Stage

The Shihezi Stage corresponds to the Bathonian, the Callovian, and the lower part of the Oxfordian. The palaeontological assemblage of the Xishanyao Formation in the standard section follows (Jiang et al., 2008b; Deng et al., 2010). The bivalves *Kija* flourishes, including *Kija kweichouensis*, *K. ovalis*, *Ferganoconcha sibirica*, *Unio zhunggarica*, *Pseudocardinia baichengensis*, *Sibireconcha*, and others. This assemblage also is known from the Yan'an Formation, the Longmen Formation, the Haifanggou Formation, the Hongqin Formation, the Yushanjian Formation, and the Zhangping Formation Among them, *F. sibirica* is an important bivalve form from the Longmen Formation (the so-called Jiulongshan Formation in northern Hebei Province) and from the Haifanggou Formation, and it is the only bivalve to have been discovered in the Daohugou biota. *Triglypta ziliujingensis* and *T. complanata* are common conchostracans in this stage and belong to the lower part of *Triglypta ziliujingensis* assemblage (Liao et al., 2017). This stratum correlates to the Yaojie Formation, the Yan'an Formation, the upper section of the Dameigou Formation, the Haifanggou Formation, the Longmen Formation, the Yangshuzhuang Formation, and the Hanshan Formation. Fossil plants are mainly ferns, followed by some ginkgo and conifers. The true fern *Cladophlebis* is the most prosperous, and *Coniopteris* are abundant, including representatives of the *Coniopteris hymenophylloides*, which are the flourishing stage of the *Coniopteris-Phoenicopsis* flora. The pollen and spores show the *Cyathidites-Neoraistrickia-Piceaepollenites* assemblage.

The Shihezi Stage is an important coal-accumulating stage. For example, the Xishanyao Formation and the Yan'an Formation are the most important coal-bearing strata in China (Wang et al., 1994). Coal-bearing sediments, such as the Yima Formation, the Fangzi Formation, the Haifanggou Formation, and the Longmen Formation, also developed in eastern China. It indicates that the main Jurassic coal deposits in China do not correspond to the east and the west. The main coal beds in the west (such as the Junggar Basin and the Ordos Basin) and in the central part of North China developed during the Shihezi Stage, whereas the main coal beds in the northern part of North China developed during the upper part of the Liuhuanggou Stage. From the Liuhuanggou Stage to the Shihezi Stage, the mountains and plateaus in eastern China have gradually eroded and flattened. Coal-bearing strata began to develop on the southern edge (such as the Zhongshan Formation) and the northern edge (such as the Beipiao and Yaopo Fms.). This period developed into a coal-forming basin in the central part of North China, and the northern margin of North China rose again in the Shihezi Stage. The new basin-mountain systems are mostly small graben basins and do not have large-scale coal-forming conditions.

Due to the lack of large-scale volcanic activity, the isotope chronology of the Shihezi Stage is limited. Clear volcanic strata (e.g., andesite, rhyolite, and tuff) are evident in the north margin of North China and Northeastern China, including the Haifanggou Formation, the Longmen Formation, and the Wanbao Formation Although the isotope chronology of the Haifanggou Formation is relatively limited, it provides important evidence for the determination of the ages of the bottom and top boundary of the Shihezi Stage. The Ar-Ar age of the lower tuff layer of the Haifanggou Formation at Beipiao is 166.7±1.0 Ma (Chang et al., 2014), the tuff is 165.0±1.2 Ma in the Dahugou bed (Yang and Li, 2008), and the volcanic rock is 164±4 Ma in the lower part of the Reshuitang bed at Lingyuan (Liu Y et al., 2006).

Recently, we dated the zircon U-Pb age of 167.1±0.9 Ma from the tuff interbeds of the bottom conglomerate and 161.7 ±1.9 Ma from the topmost tuffaceous breccia of the Haifanggou Formation at Beipiao. Therefore, the age of the Haifanggou Formation can be limited to approximately 168–161 Ma. In addition, the Wanbao Formation in the Longjiang Basin of the Da Hinggan Mountains in western Heilongjiang Province is composed primarily of glutenite, pyroclastic rocks, and shed coal. The zircon U-Pb ages are 165.2±1.7 Ma and 162.1±1.6 Ma, respectively, which matches the age of the Haifanggou Formation (Zhang et al., 2018). Due to the comparability of the biostratigraphy of the Haifgougou and Xishanyao Fms., the top and bottom age of the Haifanggou

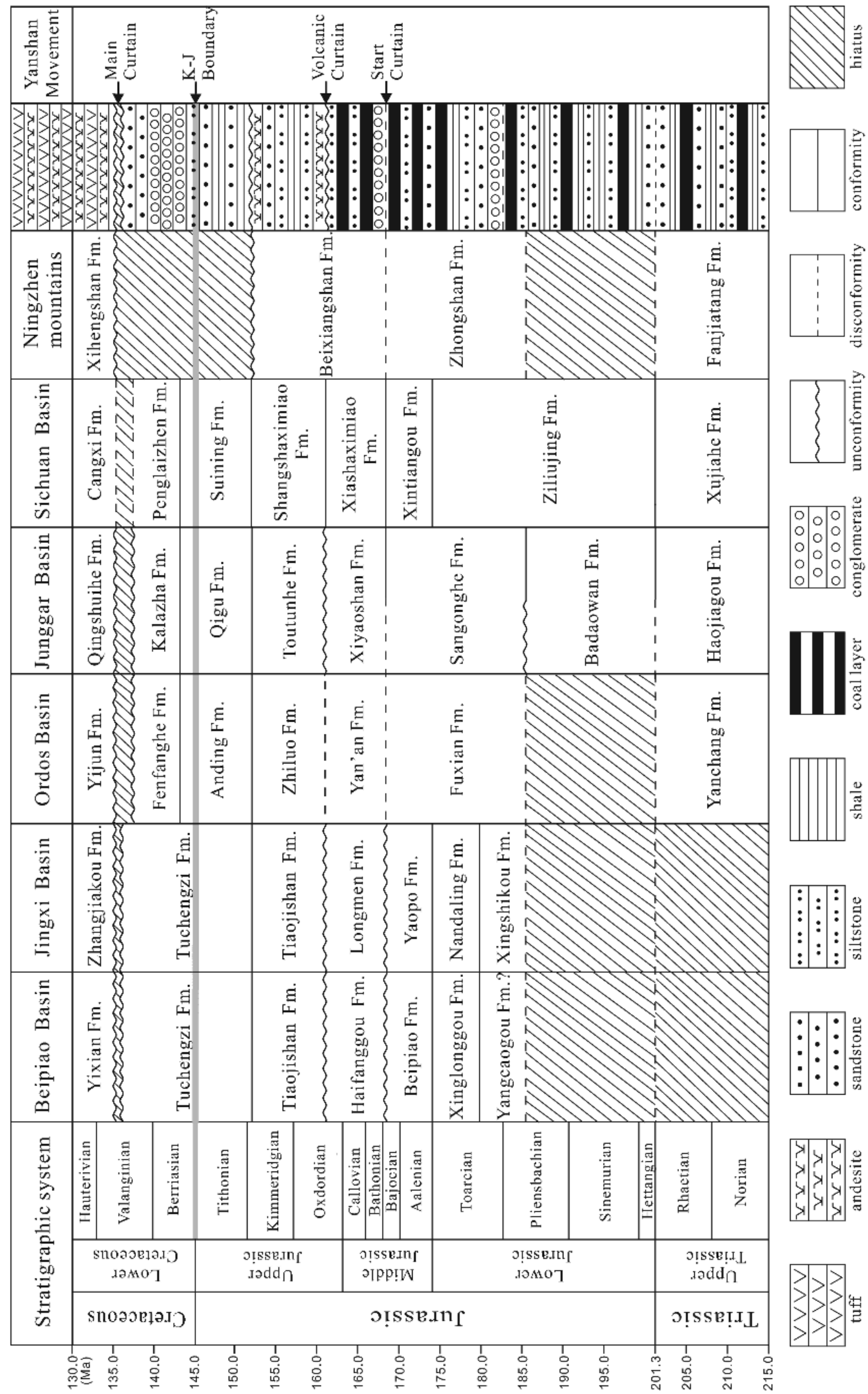

Figure 2 The stratigraphic correlation of the representative Jurassic terrestrial basins of China.

Formation generally limits the age of the Shihezi Stage.

3.4 The Manas Stage

The Manas Stage corresponds to the middle-upper section of the Oxfordian and the lower section of the Kimmeridgian. The palaeontological assemblage of the Toutunhe Formation at the standard section follows (Jiang et al., 2008a; Deng et al., 2010). The bivalves *Psilunio* are abundant, *Kija* declines, the common Jurassic forms, such as *Psilunio jingyuanensis*, *P. ovalis*, and *Cuneopsis sichuanensis*, appeared, and *Ferganoconcha* is still existent. This assemblage also appeared in the Wangjiashan Formation, the Xiashaximiao Formation, the Shangshaximiao Formation, the Ma'ao Formation, and the upper section of the Shiti Formation Conchostracans still belong to the *Triglypta ziliujingensis* assemblage, including *Triglypta manasica*, *T. tianshanensis*, *T. ziliujingensis*, and *Qaidamestheria shanshanensis*. Ostracods display an assemblage as *Darwinula sarytirmenensis-D. magna-Timiriasevia*. Gastropods display an assemblage as *Viviparus qiketaiensis-Amplovalvata suturalis*. The fossil plant *Coniopteris simplex* is abundant, which indicates the declining stage of the *Coniopteris-Phoenicopsis* flora. The pollen and spores show an assemblage of *Cyathidites-Concavissimisporites-Classopollis*. The charophytan assemblage is *Aclistochara abshirica-A. stellerides-A. nuguishanensis*.

The isotope chronology of the Toutunhe Formation is limited. The researchers analyzed the Mesozoic detrital zircons in the Junggar Basin and believed the youngest zircon came from the Toutunhe Formation in 150±4 Ma, and appear to have a peak age of 162 Ma, which represents the impact of the Yanshan Movement in the Junggar Basin (Yang et al., 2013). In recent years, the researchers obtained the zircon U-Pb age of 159 Ma in the lower layer of the Toutunhe Formation and calculated that the bottom age of the Toutunhe Formation was no more than 161.2 Ma (Fang et al., 2015). The Toutunhe Formation in the Junggar Basin and the Tiaojishan Formation in the Yanliao area are highly correlated in biostratigraphy and isotopic geochronology.

The isotope age range of the Tiaojishan Formation is extremely wide, ranging from 127 Ma to 188 Ma (Wang et al., 2001; Zhang et al., 2009). Due to the frequent capture zircons from the Haifanggou Formation, the zircon U-Pb age in the Tiaojishan Formation is often deemed to be older (Liu J et al., 2006), and the volcanic activity during the Haifanggou period is always neglected (Huang, 2015). This article does not aim to analyze all of the isotope ages of the Tiaojishan Formation The divergence mostly is caused by deviations in stratigraphic identification and methods of dating. The boundary between the Tiaojishan Formation and Tuchengzi Formation is about 153 Ma (Liu J et al., 2006) and will be introduced in detail later. In recent years, a large number of isotopic chronology studies have proven that the age of bottom volcanic rocks of the Tiaojishan Formation is approximately 160–161 Ma (Davis et al., 2001; He et al., 2004; Chang et al., 2009; Liu Y et al., 2012). The CA-ID-TIMS dating of tuff interlayers of the Tiaojishan Formation reveal that it contains zircons nearly 161 Ma (Chu et al., 2016). Therefore, the age of the Tiaojishan Formation is roughly 161–153 Ma. Some researchers believe that the volcanic rocks of the Tiaojishan Formation exhibit diachroneity, and the age of eruption in different regions is significantly different. For example, the bottom age of the Tiaojishan Formation in the Hunyuan Basin is 152.77±0.63 Ma (Li et al., 2015). In fact, this proves only that the volcanic eruption of the Tiaojishan period is isochronous. The basalt-andesite that is dated like the previous research often represents the late volcanic eruption of the Tiaojishan period, which corresponds to the upper boundary age of the formation as 153 Ma. Other researchers have suggested that the volcanic rock-sedimentary rock strata of the Tiaojishan, Tuchengzi, and Zhangjiakou periods are all diachroneity (Davis, 2005), but this is obviously related to large errors in isotope dating or misidentification of strata (Liu et al., 2018). The large-scale magmatism in the early Tiaojishan period was 161–159 Ma. This magmatism is characterized by molten breccia, rhyolite, trachyte, lava, and other volcanic andesite rocks. The late large-scale magmatic activity occurred at about 154–153 Ma. from lava to basalt-andesite to basalt in the late Tiaojishan period. Several small-scale volcanic eruptions occurred in the intervening time. An unconformity often appears between the Tiaojishan Formation and the underlying Haifanggou Formation/Longmen Formation Carbonaceous siltstones have developed above this unconformity and under volcanic rocks in some areas, such as in the Ningcheng Basin and the Liujiang Basin. This layer sometimes yielded siliciffied wood that represent a layer of ancient soil and the vegetation landscape at the beginning of the Tiaojishan period (Huang, 2015, 2016). Therefore, the age of the unconformity is slightly earlier than the initial age of the volcanic rocks in the Tiaojishan Formation This paper tentatively estimated the unconformity to be 161 Ma, which is highly consistent with the estimated age of 161.2 Ma (Fang et al., 2015) at the bottom of the Toutunhe Formation in the Junggar Basin.

3.5 The Fifth Jurassic Stage

According to National Stratigraphic Commission's recommendations, the terrestrial upper Jurassic chronostratification is exemplified by the section of the Tuchengzi Formation at the Jinlingsi-Yangshan Basin in the northwest Liaoning Province and establishes the Tuchengzi Stage. A large number of conchostracans, ostracods, plants, pollen and spores have been discovered in the Caijiagou Section (Wang and Ji, 2008). They indicated that the lower part of the

Tuchengzi Formation corresponds to the age of the upper Bathonian and Callovian and the upper part corresponds to the age of the Oxfordian (Wang and Ji, 2008), which is inconsistent with recent research on biostratigraphy and isotope chronology. The authors of this paper believe that the Jurassic-Cretaceous boundary should be located in the lower part of the Tuchengzi Formation. The fossils of the Tuchengzi Formation are divided into two assemblages. The lower part is the *Pseudograpta-Sinograpta-Monilestheria* conchostracan assemblage and the *Darwinula-Damonella-Timiriasevia* ostracod assemblage. The upper part is the *Yanshanoleptestheria-Pingquania-Lingyuanella* conchostracan assemblage and the *Djungarica-Mantelliana-Damonella-Stenestroemia* ostracod assemblage (Wang and Ji, 2008; Wang et al., 2013). The *Darwinula* and *Timriasevia*, which are abundant in the lower assemblage, inherited the characteristics of the Tiaojishan Formation, which has Jurassic characteristics, and the appearance of *Djungarica* in the upper assemblage may signify the beginning of the Cretaceous. The lower conchostracan assemblage of the Tuchengzi Formation is closely related to that of the Zhangjiakou-Dabeigou Formation. *Nestoria* and *Sentestheria* would have evolved from the *Pseudograpta* and *Monilestheria* of the Tuchengzi Formation (Wang et al., 2013). The upper conchostracan assemblage is associated with the eosestheriids that feature Cretaceous characteristics. Therefore, the Jurassic-Cretaceous boundary should cross between these two biological assemblages of the Tuchengzi Formation. The depositional stages and sedimentary facies of the Tuchengzi Formation are different in different regions. For example, the Jurassic-Cretaceous boundary should be located in the upper part of Member 1 of the Tuchengzi Formation at Jin-Yang Basin. The editorial committee of the Chinese Stratigraphic Table of the Chinese Stratigraphy Committee (2014) determined that the upper Jurassic stratum in China should correspond in age to the Tuchengzi Formation, but the stage has not been established. They mainly consider that it is difficult to determine an exact attribution of the Tuchengzi Formation. Considering the integrity of the chronostratigraphic, it is treated as a stage of the Late Jurassic (Wang et al., 2014). Given that the name of a stage and a formation cannot be synonymous, Wang et al. (2013) proposed to rename the Tuchengzi Stage to Sanbaoying Stage.

Deng et al. (2015) observed that the *Classopollis* pollen content near the top of the Toutunhe Formation increased significantly, suggesting a global climate-drying event in the Late Jurassic. This climate event had a wide range of impacts in China, leading to significant changes in the biota. For example, the conchostracan assemblage at the top of the Toutunhe Formation, the Qiaketai Formation, and the Wangjiashan Formation have undergone significant changes, and *Sinokontikia*, *Turfanograpta*, *Tianshanograpta*, and *Paleoleptestheria* have appeared (Wang, 1985a; Deng et al., 2003). Large-scale volcanic eruptions took place in the northern part of North China during the late Tiaojishan period, and thus fossil features were unclear. The late assemblage of the Yanliao biota, however, was nearly extinct at this time. In the standard section of the Manas Stage, contact between the Toutunhe Formation and the Qigu Formation is integrated and the boundary is inseparable. In this case, the lithostratigraphy used as the boundary standard of the stage is unclear. Therefore, we suggest that the boundary line of the pollen content of *Classopollis* increased significantly and that the appearance of new conchostracan assemblages can be used to divide the Manas Stage and the Fifth Stage. The boundary age is about 155 Ma.

Swisher III et al. (2002) first determined the isotope age of the Tuchengzi Formation. The Ar-Ar age of the upper section of volcanic ash feldspar single crystal was 139.4±0.19 Ma, indicating that the Jurassic-Cretaceous boundary crossed the Tuchengzi Formation. The Tuchengzi Formation and the Tiaojishan Formation are in contact with disconformity or integration. Its bottom age must be constrained by the age at the top of the Tiaojishan Formation and at the bottom of the Tuchengzi Formation A series of zircon U-Pb age data were obtained in different regions at the top of the Tiaojishan Formation, including 153.6±3.8, 152.6±0.3, 153.3±3.3, and 152.5±0.4 Ma (Cope, 2003; Davis, 2005; Liu J et al., 2006). The zircon U-Pb ages of 151.5±3.4, 152.3±2.9, 151.8±3.3, and 153.7±1.1 Ma have been obtained in deferent areas at the bottom of the Tuchengzi Formation (Cope, 2003; Cope et al., 2007; Xu H et al., 2012). Therefore, it was reasonable for Liu et al. (2006) to set the boundary age between the Tuchengzi and Daishan Fms. at about 153 Ma.

In contrast to the previous knowledge of Jurassic biostratigraphy, the present paper combined the recent progress in isotope chronology to significantly shift the upper-middle Jurassic strata, and thus developed relatively complete and continuous terrestrial Jurassic strata in the southern margin of the Junggar Basin. According to the Qigu Formation, the Fifth Stage can be established, while the Jurassic-Cretaceous boundary should appear across the upper part of the Qigu Formation Some researchers obtained zircon U-Pb ages 157–167 Ma for the Qigu Formation (Wang and Gao, 2012; Deng et al., 2015), but these likely are recycled zircons. The zircon U-Pb age of 151 Ma in the lower part of the Qigu Formation may represent its true age (Fang et al., 2015), which is consistent with the age of the Tuchengzi Formation. Some researchers have analyzed the detrital zircon in the Qigu Formation, yielding a small peak of 159 Ma and the youngest zircon of 151 Ma (Yang et al., 2012). The 159 Ma recycled zircon should indicate magmatic activity in the Toutunhe Formation, and the youngest zircon at 151 Ma signifies the age of the Qigu Formation. The palaeontological assemblages of the Qigu Formation are as follows: the ostracod assemblage is *Darwinula-Djungarica-Timiriasevia*, the gastropod assemblage is *Valvata zhongjiangensis*-*Cincinna penglaizhenensis*-*Amplovalvata* sp., and the pollen and spores assemblage is *Classopollis*-*Pinuspollenites* (Deng et al., 2010). The ostracods in the Qigu Formation still contain a distinct assemblage of *Darwinula*-*Timiriasevia*, and *Djungarica* has appeared in the upper section (Deng et al., 2003). The clear presence of *Djungarica* can indicate the start of the Cretaceous. The Qigu Formation is correlated in age to the Suining Formation in the Sichuan Basin, which means that the Jurassic-Cretaceous boundary should appear across the upper section of the Suining Formation. Recently, some researchers have suggested that the age of the Suining Formation is younger than 120 Ma through zircon U-Pb dating (Liu G et al., 2017). These zircons, however, likely were affected by late metamorphism and did not reflect the true age. In the original text, it is evident that the four zircons clustered around 145 Ma may be close to the real age of this section of the Suining Formation.

3.6 Marine Jurassic

The Marine Jurassic strata of China is not well-developed. After the Indosinian Movement, large-scale retreats occurred in South and Southwest China. New Tethys Ocean is mainly distributed in Tibet, southern Qinghai, southwestern Xinjiang, western Yunnan, and central Guangdong, Hong Kong, southern Hunan, western Fujian, and Taiwan. In the eastern part of Heilongjiang, the paleo-Pacific oceanic marine and marine-terrigenous interphase strata were developed (Sun et al., 2000). The transgressed areas in Guangdong, southern Hunan, and southwestern Fujian developed in the early Early Jurassic, whereas the central Hunan and Guizhou provinces formed a gulf and lagoon environment (Wang et al., 1994).

The Jurassic chronostratigraphic system in the International Stratigraphic Table is based primarily on the first occurrence of the specific ammonite zone in the European marine Jurassic. The Jurassic marine strata of China are relatively complete in the Qinghai-Tibet area and are rich in fossils. The basic appearance of the ammonites is similar to that of Europe, and it is a critical area for studying the Jurassic chronostratigraphy in China. Thus, some established assemblages can be compared with the standard ammonite zone of the Tethys area, but the research status does not yet specify the requirements for building conditions specified by the “International Stratigraphy Guidelines” (Sun et al., 2000). Chinese scholars also have established the brachiopods and marine bivalve biostratigraphic zone in the Qinghai-Tibet area as well as the marine bivalves, radiolarians, and dinoflagellates biostratigraphic zones in the east of Heilongjiang Province (Sun et al., 2000; Xu et al., 2003).

Marine-terrigenous interphase deposits, particularly marine fossil interbeds in nonmarine strata, are important. The Jurassic marine-terrigenous interphase strata of China are limited to eastern Heilongjiang, southern Qinghai, southern Tibet, and western Yunnan, where it is rare to find ammonites in the marine interbed, which presents significant challenges when comparing the marine-terrestrial Jurassic system (Deng et al., 2003). The comparison of marine and terrestrial Jurassic systems of China is based on specific research foundations. Some researchers have attempted to combine the ammonite assemblages of Tethys Himalayan, the bivalve assemblage of the Gangdise area, and the marine and nonmarine bivalves of the southern Qinghai region to provide an approximate age for the terrestrial Jurassic system (Deng et al., 2003).

4. Comparison of Jurassic strata of China

Jurassic terrestrial strata are widely developed in China, but they often are deposited in isolated small basins. The outcrop is often incomplete and the lithology is varied. The fossil features have regional difference, and the identification of the same type of fossils is often in disagreement. Feasible isotope dating conditions are lacking. Thus, the division and comparison of the continental Jurassic system in China remain confusing.

4.1 Terrestrial Triassic-Jurassic Boundary in China

The Triassic-Jurassic boundary-type strata is located in the Kuhjoch Section (GSSP) of the Karwendel Mountains in Austria, which defines the bottom boundary of the Jurassic as the first occurrence of the ammonite subspecies *trolicum* Hillebrandt and Krystyn of *Psiloceras spelae* Guex (Deng et al., 2010). The marine Triassic-Jurassic boundary in China is visible in multiple sections in Tibet and may compared with the standard ammonite zone in Tethys. Among them, *Psiloceras* is found at the bottom of the Ridang Formation in the Longzi County and bottom of the Wulong Formation at the Nielamu Section. *Psiloceras* is the representative of the Planorbis Zone at the bottom of the Hettangian Stage in Europe (Sun et al., 2000).

The division of the terrestrial Triassic-Jurassic boundary in China remains controversial. The Lower Jurassic strata in the eastern and central China are missing, and the Triassic-Jurassic sediments in the Junggar Basin, the Qaidam Basin, and the Sichuan Basin are relatively continuous. The division of the Triassic-Jurassic boundary in the Junggar Basin is controversial. For example, Zhang (1983) believed that the age of the Badaowan Formation is the Late Triassic, and the boundary of the Triassic-Jurassic system is above the Badaowan Formation. Huang (2006) believed that the boundary should be within the Haojiagou Formation. Most researchers believe that the boundary should be between the Haojiagou and Badaowan Fms. (Deng et al., 2003; Lu and Deng, 2005;

Sha et al., 2011), which is between the two plant assemblages of *Hausmannia-Clathropteris minoria* and *Todites princeps-Clathropteris elegans* and the bottom of the pollen and spores assemblage *Asseretospora-Dictyophyllidites-Concavisporites* (Deng et al., 2010). According to the study of plants, megaspores, conchostracans, and bivalves, the possibility that the upper part of the Haojiagou Formation belongs to the Jurassic period cannot be ruled out (Deng et al., 2003). Recently, some researchers have studied the detailed cyclic stratigraphy of the Haojiagou and Badaowan Fms. in the Haojiagou Section. They believed that the boundary of the Triassic-Jurassic system and the end-Triassic mass extinction events are extremely close and are located near the bottom of the Badaowan Formation. This boundary is slightly higher than the Haojiagou Formation-Badaowan Formation boundary (Sha et al., 2015). The editorial committee of the "Chinese Stratigraphic Table" (2014) of the National Stratigraphy Commission set the bottom of the Yongfeng Stage at 199.6 Ma.

In the Sichuan Basin, it generally believed that the boundary of the Triassic-Jurassic system is located between the Xujiahe Formation and the Ziliujing Formation (Wang et al., 2010; originally noted as the Zhenzhuchong Formation). Recently, some researchers conducted a comprehensive study of magnetic chronology, astronomical cycles, and biostratigraphy on the Xujiahe Formation of multiple sections in the Sichuan Basin. They believed that the age of the Xujiahe Formation began at the end of the Norian to the Triassic-Jurassic Boundary. This research has further confirmed that the boundary of the Triassic-Jurassic in the Sichuan Basin is located between the Xujiahe Formation and the Ziliujing Formation (Li M et al., 2017; originally noted as that Zhenzhuchong Formation). According to the suggestion of "Lithostratigraphy of Sichuan Province," the present paper adopts the scheme of incorporating the Zhenzhuchong Formation into the Ziliujing Formation (Sichuan Bureau of Geology and Mineral Resources, 1997; National Stratigraphy Commission, "Chinese Stratigraphic Table" Editorial Committee, 2014).

Due to the lack of volcanic activity near the Triassic-Jurassic boundary in the previously noted areas, isotope dating is impossible. The current stratigraphic comparison mainly relies on the study of continental biostratigraphy and paleomagnetic data. On the basis of traditional stratigraphic divisions, the Triassic-Jurassic boundary in the Junggar Basin temporarily was placed between the Haojiagou and Badaowan Fms., and in Sichuan Basin was placed between the Xujiahe and Ziliujing Fms.

4.2 Terrestrial Jurassic-Cretaceous boundary of China

Continental deposition primarily occurs near the Jurassic-Cretaceous boundary in China and related strata generally are missing in South China. It is generally believed that the lithology of the relevant strata in the Junggar Basin and the Ordos Basin are relatively coarse and contain limited fossils, making it difficult to make stratigraphic comparisons. In contrast, the study of the Jurassic-Cretaceous biostratigraphy in the Yanliao area is more in-depth and has multiple sets of isotopic dating data. Therefore, the Tuchengzi Formation holds the key to determining the continental Jurassic-Cretaceous boundary in China.

The age of the Tuchengzi Formation is extremely controversial; in particular, the conclusions of biostratigraphy and isotope geochronology have displayed significant differences (Wang et al., 2013). Previously, the studies on biostratigraphy primarily believed that the Tuchengzi Formation belonged to the Middle Jurassic (Shen and Chen, 1984; Wang, 1998; Wang et al., 2004) or the Late Jurassic (Wang and Li, 2008; Wang et al., 2013; Deng et al., 2017). Today, more scholars believe that the continental Jurassic-Cretaceous boundary is located within the Tuchengzi Formation (Sun et al., 2007; Xu et al., 2014; Deng et al., 2015; Liu et al., 2018), but most researches have suggested that the boundary is located in the upper part of the Tuchengzi Formation (Ji et al., 2006; Wan et al., 2013; Li and Matsuoka, 2015). The fossils of the Tuchengzi Formation are not abundant, and invertebrates are characterized by *Pseudograpts-Cetacella* (Wang et al., 2004). Additionally, limited fossils are known from the underlying Tiaojishan Formation. Therefore, it is difficult to establish a continuous fossil zone in this area. It is also difficult to make precise comparisons with marine fossils from Europe. In recent years, a large number of invertebrate fossils have been found in the Linglongta bed of the Tiaojishan Formation, including conchostracans, ostracods, bivalves, gastropods, and insects (Duan et al., 2009; Huang, 2015, 2016). These fossils provide evidence for an understanding of the fossil evolution of the Tuchengzi Formation. The biostratigraphic analysis of the continental Jurassic-Cretaceous boundary in China is described later.

An angular unconformity exists between the Tuchengzi and Zhangjiakou Fms., which is the Yanshan Movement, Curtain B. As mentioned earlier, the age of the bottom Tuchengzi Formation is around 153 Ma, and the age of its top generally is considered to be 137–136 Ma (Zhang et al., 2009; Xu H et al., 2012; Wang et al., 2013), which restricts the time of deformation of the Yanshan Movement, Curtain B. The age of the bottom Zhangjiakou Formation is about 135 Ma (Davis et al., 2001; Niu et al., 2004; Zhao et al., 2004b). Although the lithofacies and stages of the Tuchengzi Formation are different in different regions, the top and bottom marks are relatively clear. The bottom of Tuchengzi Formation generally is covered with volcanic rocks and pyroclastic rocks of the Tiaojishan Formation, or ancient strata, and its top is located below the unconformity of the

Yanshan Movement, Curtain B. The age range is about 153–136 Ma. The Jurassic-Cretaceous boundary (145 Ma) is located in time at the point of the Tuchengzi Formation (153–136 Ma). The middle-upper part of the Tuchengzi Formation, however, is mostly composed of alluvial fan conglomerate or eolian sandstone, and the deposition rate is rapid. Therefore, the layers of 145 Ma should be located at the lower part of the Tuchengzi Formation in most basins. The isotopic age of the middle part of the Tuchengzi Formation is limited. For example Zhang et al. (2005) obtained the zircon U-Pb age (142.6±1.3 Ma) of the tuffaceous lava at the bottom of the Member 2 of the Tuchengzi Formation in Xiaoying, Luanping County. Zhang H et al. (2008) obtained the bottom ages of 146.5±1.7 Ma and 147.4±2.2 Ma in the Chengde Basin and the Jin-Yang Basin, which may represent the age of the middle layers of the Tuchengzi Formation (Xu et al., 2014). To date, there are relatively complete isotopic chronological sequences in the Tuchengzi Formation in the Beipiao area. For example, the middle part of Member 3 is 137 Ma, the lower part of Member 3 is 139 and 140 Ma, the bottom part of Member 2 is 142 Ma, and the top of the Tiaojishan Formation is 154 Ma (Xu et al., 2014). The age of the top Tuchengzi Formation is 136 Ma, the upper section is 140 Ma and the middle section is 143 Ma, and the top of the Tiaojishan Formation is 154 Ma in the Luanping Basin (Zhang et al., 2005; Xu et al., 2014). Zhang H et al. (2008) believed that an obvious volcanic activity occurred in northern Hebei Province and western Liaoning Province during the period of 142–141 Ma. The corresponding stratum is the top of Member 1 of the Tuchengzi Formation. Therefore, the continental Jurassic-Cretaceous boundary should cross the lower parts of the Tuchengzi Formation. According to the National Stratigraphy Commission, "Chinese Stratigraphic Table" Editorial Committee (2014), it is incorrect to link the age of the Tuchengzi Formation to the whole Upper Jurassic.

The Jurassic-Cretaceous boundary in the Junggar Basin generally is regarded as being below the Qingshuihe Formation (Tugulu Group). The Kalazha Formation generally is considered to belong to the middle Late Jurassic and it lacks the Tithonian deposits (Eberth et al., 2001; Deng et al., 2010; Fang et al., 2016; Sha et al., 2016). The Tuchengzi Formation of Jin-Yang and Beipiao basins in the west of the Chaoyang area, Liaoning Province, can be divided into three members: Member 1 includes variegated fine clastic rock, which is a lake shore with shallow lake sediment; Member 2 includes variegated coarse-grained rocks, such as gray-purple conglomerate, which is characterized by alluvial fan deposition; and Member 3 mainly includes eolian deserts or dry lakes (Xing et al., 2001). The lithofacies of the Tuchengzi Formation vary in different basins, but its age range is consistent (Xu et al., 2014). The Jurassic-Cretaceous sediments in the Junggar Basin are comparable to the Yanliao region. The Qigu Formation features variegated fine clastic rock, and the Kalazha Formation is dominated by gray-brown glutenite, both of which correspond in age to the Tuchengzi Formation. Recent isotopic geochronological studies have revealed that the zircon U-Pb age of the lower part of the Qigu Formation is approximately 151 Ma (Fang et al., 2015), confirming its association with the Tuchengzi Formation Therefore, the Jurassic-Cretaceous boundary in the Junggar Basin should be located in the upper part of the Qigu Formation. The Anding Formation in the Ordos Basin features fine clastic rock, and the Fenfanghe Formation is dominated by glutenite, both of which also correspond in age to the Tuchengzi Formation. The Jurassic-Cretaceous boundary should be located in the upper part of the Anding Formation in the Ordos Basin. Therefore, the view that the Jurassic strata generally are lacking within the Tithonian (e.g., Deng et al., 2017) is not supported.

The lack of sediment below the Qingshuihe Formation in the Junggar Basin and below the Yijun Formation in the Ordos Basin corresponds in age to the Yanshan Movement, Curtain B. In addition, in the early Early Cretaceous, a set of aeolian rocks of the Valanginian-Hauterivian developed in northern China. The zircon U-Pb age in the lower part of the eolian sandstone of Member 3 of the Tuchengzi Formation is about 137.4 Ma (Xu et al., 2013). These eolian deserts also developed in the Lower Cretaceous Luohe Formation in the Ordos Basin (Xu et al., 2013) and in the Lower Tugulu Group in the Wucaiwan area, Xinjiang (Eberth et al., 2010). Thus, a series of red sediments and eolian deserts commonly developed in the northern part of China during the Jurassic-Cretaceous boundary period, which represents an arid climate.

4.3 Comparison of Jurassic Strata in Yanliao Area

The Yanliao region (western Beijing, northern Hebei Province, and western Liaoning Province) is a well-studied area of the Jurassic strata and biota in China, including its biostratigraphy and isotopic chronology. According to the in "Geological Studies of Xishan, Beijing" (Ye, 1920), the Jurassic system of West Beijing can be divided into the Mentougou Series, the Jiulongshan Series, and the Tiaojishan Member.

Wong proposed the concept of the Yanshan Movement in 1927 based on the geological knowledge of West Beijing. The Beipiao Basin of western Liaoning was a classic area for the study of the Jurassic strata. In 1928, Wong determined a definition of the Yanshan Movement based on a new understanding of the geological structure of the Beipiao Basin (Wong, 1927, 1928). The Jurassic strata of the Beipiao Basin was divided, from bottom to top, as follows: Yangcaogou Formation-Xinglonggou Formation-Beipiao Formation-Haifanggou Formation-Tiaojishan Formation (Lanqi Formation)-Tuchengzi Formation, which corresponded in age to Xingshikou Formation-Nandailing Formation-Yaopo Formation-Longmen Formation-Jiulongshan Formation-Tiaojishan Formation-Tuchengzi Formation (Houcheng Formation) in the Jingxi Basin.

According to previous analysis, the age of the Tuchengzi Formation is about 153–136 Ma. Its top boundary is a regional unconformity (Yanshan Movement, Curtain B), and the sedimentary discontinuous time is 136–135 Ma. Contact between the Tuchengzi Formation and the Tiaojishan Formation is integrated or it forms a disconformity. The boundary line is not always easily distinguishable, and the age is approximately 153 Ma (Liu J et al., 2006; Xu et al., 2014). The bottom of the Tiaojishan Formation is also a regional interface, and sometimes an unconformity is visible (Huang, 2015). The age of this boundary is about 161 Ma and can be restricted by the isotopic age of the upper and lower rock layers. Thick layers of lacustrine interbeds between the volcanic rocks, which are rich in fossils, developed in the Tiaojishan Formation at Daxishan in Jianchang County and Guancaishan in Jianping County, Liaoning Province, and Nanshimen in Qinglong County, Hebei Province.

The bottom of the Haifanggou Formation is also a regional unconformity and is characterized by a set of synorogenic conglomerate. Thus far, the isotope age of the top rocks of the Beipiao Formation cannot be determined. The age of the tuffaceous interbed of the bottom conglomerate of the Haifanggou Formation is 167.1 Ma in our unpublished study, however, should be close to the age of the unconformity. This unconformity is estimated to be around 168 Ma in this paper. The age of the bottom of the Yungang Formation is consistent with the age of Yanshan Movement, Curtain A. coincides with that of the Haifanggou Formation (Li Z et al., 2014).

In western Beijing and northern Hebei Province, the Jiulongshan Formation is often identified as having volcanic clastic rock beneath the volcanic rocks of Tiaojishan Formation. Huang suggested that the Jiulongshan and Tiaojishan Fms. are close in age, and they are in fact phase transitions (Huang, 1954, 1960). This view has been proven by recent isotope geochronological studies (Liu J et al., 2006; Li H et al., 2014). The bottom of the Jiulongshan Formation is no older than 161 Ma. Its age is between 161 Ma and 153 Ma, like that of the Tiaojishan Formation Two-stage zircons dated between approximately 161 Ma and 154 Ma are located in the bottom tuff of the Jiulongshan Formation at the Yubai Village, western Beijing, which correspond in age to the volcanic activities in the early and late Tiaojishan periods (Li H et al., 2014). This study indicates that the Jiulongshan Formation may be relatively young and corresponds in age to the upper part of the Tiaojishan Formation The fossil-rich strata under the volcanic rocks of the Tiaojishan Formation in northern Hebei Province often are referred to as the Jiulongshan Formation. Many researchers also have attributed the Daohugou beds to the Jiulongshan Formation. These strata containing pyroclastic rocks actually are part of the Longmen Formation or the Haifanggou Formation, which contain important fossils, such as *Ferganoconcha sibirica* and *Triglypta pingquanensis* (Hebei Bureau of Geology and Mineral Resources, 1996). Some researchers have obtained zircon U-Pb age of 163.4±1.1 Ma from the Jiulongshan Formation in the Chengde Basin, which represents the age of the fossil-rich strata, but these fossils belong to the Longmen Formation-Haifanggou Formation (Chen et al., 2014). From the original images in Chen et al. (2014; see Table 1, Figures 3 and 4), these zircons actually may belong to different stages and contain some recycled zircons from the Longmen Formation. The Jiulongshan Formation and the Longmen Formation in northern Hebei Province are easily confused. The bottom of the Longmen Formation is composed of complex conglomerate, and the middle-upper parts include fine clastic rocks with pyroclastic rocks. The Longmen Formation is overlying the Yaopo Formation as well as other ancient rocks with an unconformity and underlying volcaniclastic or volcanic rocks of the Jiulongshan-Tiaojishan Formation This formation is rich in fossils, such as bivalves *F. sibirica* and conchostracans *T. pingquanensis*. A prosperous period of the *Coniopteris-Phoenicopsis* flora is dated from 168–161 Ma. The Jiulongshan Formation is a volcaniclastic rock stratum and it is a simultaneous heterogeneous

Table 1 The comparison of the Jiulongshan Formation and the Longmen Formation

<table>
<tr><th colspan="3">The major traditional opinion</th><th colspan="2">The present opinion</th></tr>
<tr><th colspan="2">Jingxi Basin</th><th>Beipiao Basin</th><th>Jingxi Basin</th><th>Beipiao Basin</th></tr>
<tr><td colspan="2">Tiaojishan Fm.</td><td>Tiaojishan Fm.
(Lanqi Fm.)</td><td rowspan="2">Tiaojishan Fm.-
Jiulongshan Fm.</td><td rowspan="2">Tiaojishan Fm.</td></tr>
<tr><td colspan="2" rowspan="2">Jiulongshan Fm.</td><td rowspan="2">Haifanggou Fm.</td></tr>
<tr><td rowspan="2">Longmen Fm.</td><td rowspan="2">Haifanggou Fm.</td></tr>
<tr><td rowspan="3">Mentougou
Coal Series
(Yaopo Fm.)</td><td rowspan="2">Longmen Fm.</td><td rowspan="3">Beipiao Coal Series
(Beipiao Fm.)</td></tr>
<tr><td rowspan="2">Yaopo Fm.</td><td rowspan="2">Beipiao Fm.</td></tr>
<tr><td>Yaopo Fm.</td></tr>
</table>

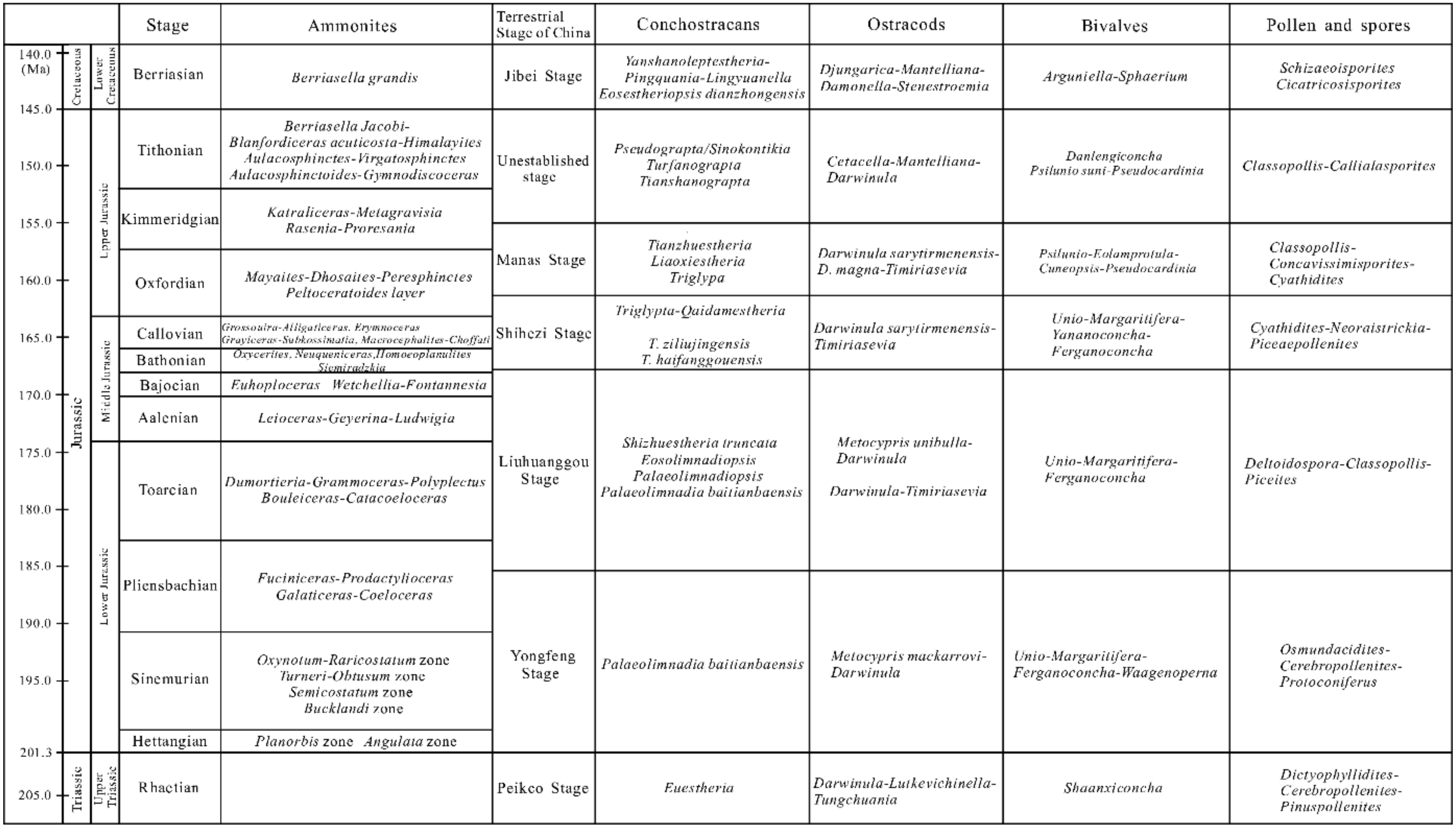

Figure 3 The stratigraphic correlation among representative Jurassic terrestrial basins of China.

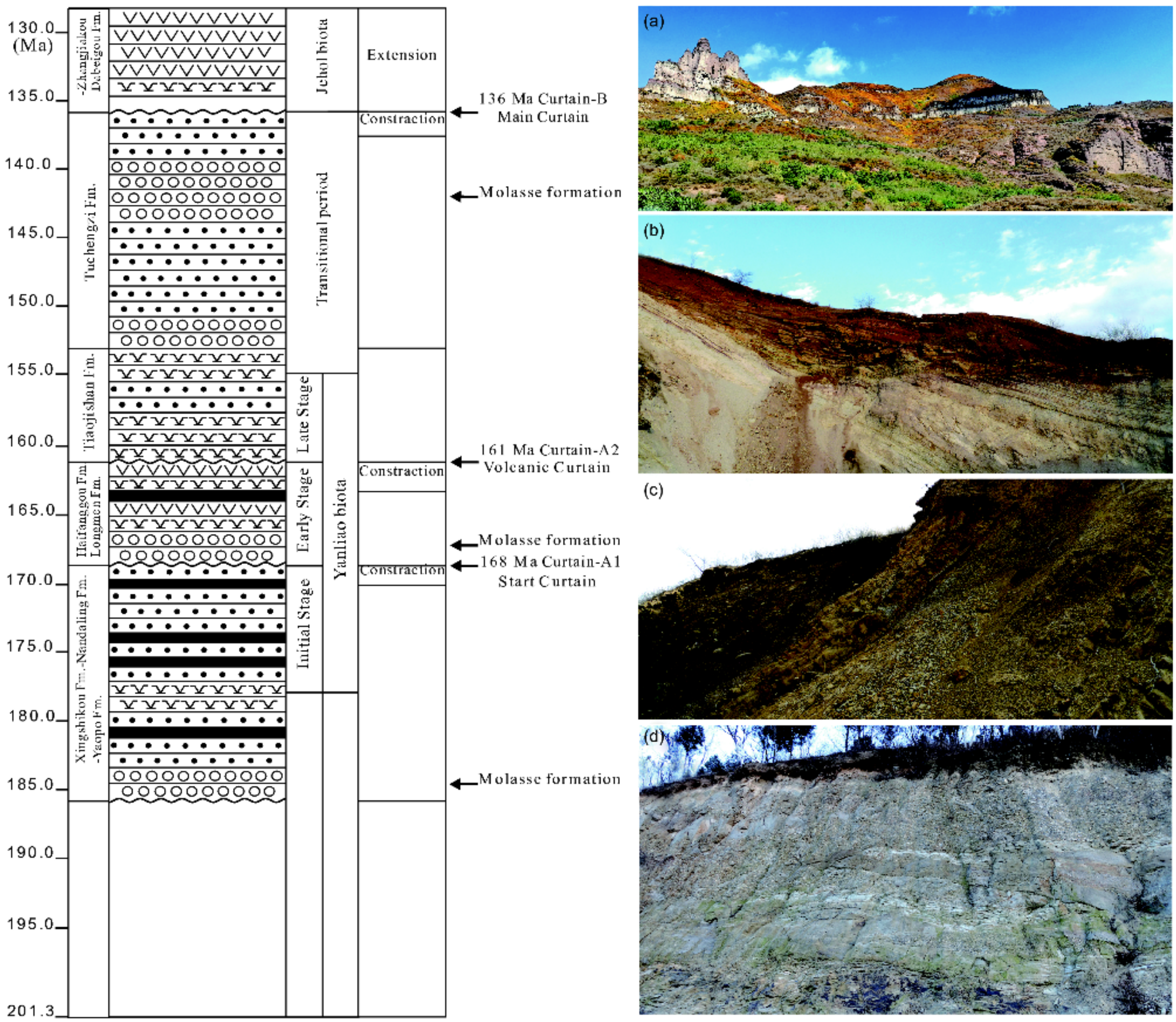

Figure 4 The relationship and geological background of the Yanshan Movement and Yanliao biota in the Yanliao region. (a) Unconformity between the Tuchengzi and Zhangjiakou Fms., (b) unconformity between the Haifanggou and Tiaojishan Fms., (c) the synorogenic conglomerates of the bottom Haifanggou Formation (left), and (d) the conglomerates of the bottom Xingshikou Formation.

deposit of the Tiaojishan Formation. It is overlying on the Longmen Formation and other ancient strata with a disconformity or unconformity interface and is underlying the Tiaojishan or Tuchengzi Fms. Fossils from the Jiulongshan Formation have not been discovered to date. The age of the Jiulongshan-Tiaojishan Formation is 161–153 Ma (Table 1).

4.4 Comparison of Jurassic strata in North China and South China

Jurassic strata in South China are widely distributed but with obvious gaps. The research on Jurassic strata in Nanjing began with the Nanjing Sandstone named after Leichofen in 1868. Xie (1928) conducted a detailed division of the strata and noted a disconformity between the Huangmaqing shale and the quartz conglomerate (the bottom of the Xiangshan Group). The Lower-Middle Jurassic Xiangshan Group may be divided further into the Zhongshan Formation (Nanxiangshan Formation) and the Beixiangshan Formation. This set of strata is widely developed in South China. The Beixiangshan Formation-Zhongshan Formation in the Ningzhen Mountains corresponds in age to following: the Luoling Formation-Moshan Formation or the Hongqin Formation-Yuetan Formation in Anhui Province; the Yushanjian Formation-Majian Formation in Zhejiang Province; the Luo'ao Formation-Linshan Formation in Jiangxi Province; the Zhangping Formation-Lishan Formation in Fujian Province; the Shiti Formation-Daling Formation in Northeast Guangxi; the Chuanjie Formation-Xialufeng Formation in the central part of Yunnan Province, and the Yuantongshan Formation-

Fanghushan Formation in Hefei Basin (Jü, 1987; Wang, 1985b; Wang et al., 1994; Deng et al., 2017). These formations cover the Upper Triassic coal-bearing strata as well as other ancient rocks. The lower units contain coal, and quartz conglomerates sometimes are seen at the bottom, which generally are attributed to the Lower Jurassic. The bottom of the upper unit sometimes also has quartz conglomerate, which gradually transition upward into red layers, which mostly are attributed to the Middle Jurassic. A disconformity always is displayed between these two units.

The lower parts of the Xiangshan Group and the relevant strata, such as the Zhongshan Formation and the Moshan Formation, are rich in fossil plants, namely Xiangshan flora. They are dominated by cycads, and are followed by ginkgo, fern, and seed fern, and contain several Triassic successive forms. It was considered to be typical Early Jurassic flora (Huang, 1983). Some researchers believe that the Xiangshan flora belongs to the late Early Jurassic that is evidenced by a small number of *Toddites* and *Coniopteris*, which are prosperous groups from the Jurassic period (Wan, 1987). *Phoenicopsis* is another common form found in the Zhongshan Formation in the Nanjing area, indicating the initial stage of the *Coniopteris-Phoenicopsis* flora. Similar plant assemblages also are found in the Majian Formation, the Lishan Formation, and the Yuetan Formation (Wang, 1985b). Some researchers believe that the plant features of the Moshan Formation are indicative of the *Ptilophyllum pecten-Todies princeps* assemblage, which suggests an age of middle-late Early Jurassic to early Middle Jurassic (Lu et al., 1985). Some bennettitalean plants have preserved their epidermis structures and have shown similar characteristics to those of the Middle Jurassic Yorkshire flora (Cao, 1998). The bivalve assemblage of *Pseudocardinia-Ferganoconcha-Tutuella* in the Moshan Formation has shown the characteristics of the middle-late Early Jurassic and early Middle Jurassic (Lu et al., 1985) or is considered to be Middle Jurassic (Wan, 1987). To summarize, the lower units of the Xiangshan Group, such as the Zhongshan Formation and the Moshan Formation, should be attributed to the Liuhuanggou Stage, with the lower part of the middle-late Early Jurassic age and the upper part of the early Middle Jurassic. The Fanjiatang Formation below the Zhongshan Formation and the Lalijian Formation below the Moshan Formation contain typical Late Triassic biota, which can be compared with the Yanchang Formation. All of these areas lack sedimentation typical of the early Early Jurassic.

The bivalves, ostracods, gastropods, and charophytans found in the Luoling Formation overlying the Moshan Formation denote Middle Jurassic characteristics (Wan, 1987). The pollen and spores of the Beixiangshan Formation also are characteristic of the Middle Jurassic (Huang, 2000). A large number of fossils found in the Luoling Formation at the Pengzhuang Section in the Hanshan County, Anhui Province (the original Hanshan Formation), have provided important evidence revealing its geological age (Lu et al., 1985). The fossil plants is characterized by the flourishing of *Coniopteris*, which indicates that it may be dated to the Late Jurassic, but it does not exclude the possibility of being dated to the late Middle Jurassic (Cao, 1985). There are two types of *Euestheria* of conchostracans (Shen, 1985). Recent studies have revealed that the *Euestheria* from the Middle Jurassic in China in fact belongs to Triglyptidae, and the true *Euestheria* mainly is found in the Triassic (Liao et al., 2017). Tiny pit-like ornaments on the carapace of the so-called *Euestheria* from the Hanshan Formation have a linear arrangement in the ventral margin, similar to *Triglypta haifanggouensis*, and belong to early representatives of the *Triglypta haifanggouensis* assemblage. Fossil insects are closely related to that of the Yanliao biota (Lin, 1985). The bivalves belong to the Middle Jurassic assemblage (Lu et al., 1985). Therefore, the Luoling Formation and the relevant strata correspond in age to the Shihezi Stage, and the main part of the formation is from the middle-late Middle Jurassic, but the upper parts may have reached to the Late Jurassic (Figure 2).

The bottom of the Zhongshan Formation and the Xingshikou Formation features a set of molasse formations from the southern and northern edges of the middle Early Jurassic eastern mountains and plateau, respectively. This molasse is characteristic of the Xingshikou Formation and presents an east-west distribution at the northern edge of North China. Such strata may have a wide range of impacts and represents a tectonic movement may have occurred before the Yanshan Movement. The comparative relationship between the conglomerate and the bottom of the Sangonghe Formation is subject to further study, but it corresponds in age to the bottom boundary of the Liuhuanggou Stage, which is the middle Early Jurassic. The disconformity between the relevant strata of Moshan Formation and Luoling Formation in South China likely represents the start of the Yanshan Movement, Curtain A1. The volcanic strata previously considered to belong to the Late Jurassic, including the Maotanchang Formation of Anhui Province and the Xihengshan Formation of Jiangsu and Anhui, in fact, may belong to the Early Cretaceous period and later to the Yanshan Movement, Curtain B (135 Ma).

5. Jurassic biostratigraphy in China

5.1 Conchostracans

Conchostracans are common and widespread fossils in the Jurassic. They are found along many horizons, with a large number of individuals and a rapid evolution. Conchostracans play a decisive role in the division and comparison of Jurassic strata. In recent years, the extensive application of scanning electron microscopy (SEM) has greatly enhanced the resolution of the delicate ornaments of the carapace of the conchostracans and has facilitated morphological comparison. The sequence of Jurassic conchostracan zones in China follows (Figure 3).

(1) Palaeolimnadia baitianbaensis Zone. *Palaeolimnadia* is a conchostracan that is representative of the late Early Jurassic in China. It is distributed mainly throughout the Liuhuanggou Stage as well as in the Yongfeng Stage. The features of conchostracans were not clear in the early Early Jurassic, and it generally is considered to belong to the *Palaeolimnadia baitianbaensis* Zone. The Badaowan Formation may contain *Palaeolimnadia* and *Euesstheria*. The Early Jurassic conchostracan groups include *P. chuangbeiensis*, *P. dachaidanensis*, *P. semicircularis*, *Euestheria taniiformis*, *Illiestheria nilkaensis*, *Bulbilimnadia bullata*, *Loxomegaglypta dafangensis*, and *Pseudolimnadia weixinensis* (Deng et al., 2003, 2010; Wang et al., 2010). The *Palaeolimnadia baitianbaensis* group is distributed mainly in the lower part of the Sangonghe Formation, the lower part of the Dameigou Formation, the Wennan Formation, and the Ma'anshan Member of the Ziliujing Formation (Deng et al., 2010; Wang et al., 2010). Several species of *Palaeolimnadiopsis* and *Eosolimnadiopsis* are found in the Fuxian Formation, which also have been attributed to the middle-late Early Jurassic (Geological Institute of the Chinese Academy of Geological Sciences, 1980b) and is called the *Eosolimnadiopsis* group (Yuan et al., 2003).

In addition, *Shizhuestheria truncata* also have been found in the Xintiangou Formation at the Sichuan Basin, which belongs to the early Middle Jurassic conchostracan group (Wang et al., 2010).

(2) Triglypta ziliujingensis Zone. Triglyptidae is the most important conchostracans of the Middle-Upper Jurassic in China. Its two groups correspond in age to the Shihezi and Manas Stages. *Triglypta ziliujingensis* Zone is equivalent to *Euestheria ziliujingensis* Zone in former literature. Previously, the Middle Jurassic small conchostracans were attributed to *Euesstheria*, but in fact, they belong to *Triglypta* (Liao et al., 2017). The conchostracans assigned within *Euestheria* in the Middle-Late Jurassic need to be reexamined.

The lower assemblage of the Triglyptids Zone mainly is distributed in the Shihezi Stage of the middle-late Middle Jurassic to the early Late Jurassic, and was especially prosperous in the early Late Jurassic. The named *Triglypta-Qaidamestheria* assemblage is characterized by relatively simple carapace ornaments (Liao et al., 2017), including *Triglypta ziliujingensis*, *T. haifanggouensis*, *T. pingquanensis*, *T. luangpingensis*, *Qaidamestheria dameigouensis*, and others. This assemblage is found mainly in the Haifanggou Formation, the Longmen Formation, the Yaojie Formation, the Yan'an Formation, the Xishanyao Formation, the Wanbao Formation, the upper parts of Dameigou Formation, the Xiashaximiao Formation, the Yangshuzhuang Formation and the Luoling Formation. *Triglypta* sp. always appear in the middle and upper parts of these formations. For example, the appearance of a large number of *T. haifanggouensis* in the Daohugou area is dated to about 163 Ma, which represents the beginning of the Late Jurassic.

The distinctive feature of Triglyptidae is that the tiny pits on the carapace surface are clustered and then are arranged linearly. The features of the line ridges are particularly evident in some forms, such as *Tianzhuestheria* (Wang, 2014). The upper assemblage of the Triglyptids Zone is distributed primarily throughout the early-middle Late Jurassic Manas Stage, which is represented by *Tianzhuestheria*, *Liaoxiestheria*, and *Triglypta*. They are distributed in the Tiaojishan Formation, the Wangjiashan Formation, the Ma'ao Formation, and the Toutunhe Formation.

(3) Pseudograpta/Sinokontikia Zone. The conchostracan variety of the Late Jurassic increased with different distributions. The representative variety is *Pseudograpta-Sinokontikia* in North China, including *Pseudograpta murchisoniae*, *Sinokontikia lianmuqinensis*, *Turfanograpta chowmincheni*, and *Mesolimnadia jinlingsiensis*, which were distributed in the lower part of the Tuchengzi Formation, the top of the Wangjiashan Formation, and the upper part of the Toutunhe Formation (Deng et al., 2003), indicating the beginning of the Manas Stage. The *Eisestheriopsis dianzhongensis* group developed in the Sichuan Basin (Wang et al., 2010), and the lower assemblage of the Tuchengzi Formation was characterized by *Pseudograpta-Monilestheria-Sinograpta* (Wang et al., 2013), both of which had local characteristics.

5.2 Ostracods

The Jurassic ostracods in China mostly have been identified as *Darwinula*. Sometimes high specific variety exists for one genus in the same layer. Since the *Darwinula* flourished from the Permian to the present day, the identification of modern types of ostracods is based mainly on the appendages and trunk characteristics. These characteristic, however, are not preserved in fossils and the carapaces were smooth and without critical structures. A previous study revealed that the Mesozoic Darwinuloidea increased from two genera to five genera (Rossetti and Martens, 1998), and therefore, many Jurassic *Darwinula* taxa need to be revised. Currently, it is difficult to systematically divide the Jurassic terrestrial biostratigraphy in China by using ostracods, but it is crucial for the Late Jurassic stratigraphic division (Figure 3).

The Early and Middle Jurassic ostracods in northern China were scarce. A few *Darwinula* sp. were found in the Badaowan and Sangonghe Fms. in the Junggar Basin (Deng et al., 2010). Some *Darwinula* sp. and *Timriasevia* sp. were found in the Fuxian Formation in the Ordos Basin (Deng et al., 2003). The assemblage *Gomphocythere Yubacunensis-G. longa* was found in the Zaoshan Formation and the Jinji Formation in Guangdong, and in the Xinqiao Formation in the southwest part of Fujian in the early Early Jurassic. The assemblage of *Darwinula-Naevicythere* was found in the late Early Jurassic in South China (Qian et al., 1987).

The ostracods from the Shihezi and Manas stages is the assemblage of *Darwinula sarytirmenensis-D. magna-Timiriasevia*, but the occurrence of *D. magna* may be relatively higher, as is common in the Manas Stage. This assemblage first appeared at the Shihezi Stage, including in the Longmen Formation, the Yaojie Formation, the Xiashaximiao Formation (Deng et al., 2003). *D. sarytirmenensis* and *Timriasevia shensiensis* were discovered in the Haifanggou Formation, and *D. sarytirmenensis* and *D. impudica* were found in the Yushanjian Formation in Zhejiang, both of which displayed an early feature of this assemblage (Su and Li, 1989). This assemblage is prosperous at the Manas Stage and has been found in the Toutunhe Formation, the Zhiluo Formation, the Wangjiashan Formation, the Ma'ou Formation, the Shangshaximiao Formation, and the Tiaojishan Formation (Deng et al., 2003).

The Tuzizi Formation is rich in fossils, which are divided into upper and lower two-ostracod assemblages. The lower part is the *Cetacella substriata-Mantelliana alta-Darwinula bapanxiaensis* assemblage and the upper part is the *Djungarica yangshulingensis-Mantelliana reniformis-Stenestroemia yangshulingensis* assemblage or the *Djungarica-Mantelliana-Damonella-Stenestroemia* assemblage (Wang et al., 2004).

The Jurassic ostracods in the Sichuan Basin have relatively continuous assemblages, with *Metocypris mackarrovi-Darwinula* in the early Early Jurassic, *Metocypris unibulla-Darwinula* in the late Early Jurassic, *Ovaticythere-Metocypris-Darwinula* in the early Middle Jurassic, *Darwinula sarytirmenensis-Metocypris* in the middle Middle Jurassic to middle Late Jurassic, and *Darwinula-Cetacella-Djungarica-Eolimnocythere* in the late Late Jurassic to the early Early Cretaceous (Wang et al., 2010).

Djungarica is an important ostracod group in the Cretaceous period of China. Its early type is distributed in the Suining Formation-Penglaizhen Formation in the Sichuan Basin and the correlating strata, such as the Tuchengzi Formation in the Yanliao region, the Hongshuigou Formation in the Qaidam Basin, and the Qigu Formation in the Junggar Basin, the Ta'ernai Formation in the southwestern of the Tarim Basin, and the Kushuixia Formation in the eastern part of Gansu Province (Pang, 1982; Wei, 1984; Deng et al., 2003; Zhao et al., 2003). These strata are located near or slightly above the Jurassic-Cretaceous boundary (below the Yanshan Movement, Curtain B). In the lower unit, including the Suining and Qigu Fms., the pioneer species of *Djungarica*, such as *D. yunnanensis* and *D. postiacuminata*, appeared in the upper sections. The upper unit, including the Penglaizhen, Hongshuigou, and Tuchengzi Fms., appeared to have a relatively diverse species of *Djungarica*. The appearance of abundant *Djungarica* may be used to signify the continental Jurassic-Cretaceous boundary and may be an important form in the first ostracod assemblage of the Cretaceous period. *Djungarica yunnanensis* was first identified in the upper section of the Hepingxiang Formation in western Yunnan Province (Ye et al., 1977), namely the Bazhulu Formation (Yunnan Bureau of Geology and Mineral Resources, 1996). Fossil features of the lower section of the overlying Lower Cretaceous Jingxing Formation are similar to that of the Tuchengzi Formation, such as the *Darwinula-Mantelliana-Damonella* ostracod assemblage, in which *Damonella ovata* and *D. depressa* also have been found in Member 3 of the Tuchengzi Formation (Pang, 1982). The typical Early Cretaceous ostracod *Cypridea* appeared in the upper section of the Jingxing Formation (Li, 1987). Therefore, the Jurassic-Cretaceous boundary may be placed below the *Djungarica* Zone at the top of the Bazhulu Formation The classification of *Djungarica* in the Hepingxiang Formation is still questionable. For example, *D. yunnanensis* has a relatively weak dorsal marginal overlap, which is different from typical *Djungarica* (Hou et al., 2002).

5.3 Bivalves

The Jurassic bivalves of China are abundant, but because of preservation reasons, specific identification is difficult. Many studies have been conducted on Jurassic bivalves in China to date, which are important when correlating terrestrial strata and comparing marine-continental stratigraphy (Figure 3).

Jurassic terrestrial bivalves in China may divided into two major assemblages, namely the Early-Middle Jurassic assemblage *Unio-Margaritifera-Yananoconcha-Ferganoconcha* and the Late Jurassic assemblage *Psilunio-Eolamprotula-Cuneopsis-Pseudocardinia* (Deng et al., 2003). The former assemblage is found in Badaowan-Sangonghe-Xishanyao Fms. in the Junggar and Turpan-Hami Basins, Xiaomeigou-Dameigou Fms. in the Qaidam Basin, Daxigou-Longfengshan Fms. in the East Qilian Mountain, Tandonggou-Yaojie Fms. in the Gansu Corridor, Fuxian-Yan'an Fms. in Ordos Basin, Beipiao-Haifanggou Fms. in West Liaoning, which are Early-Middle Jurassic strata, as well as in the Wanbao Formation in Da Hinggan Mountains, Yima Formation in Henan Province, and Yangshuzhuang Formation in Jiyuan Basin, which are Middle Jurassic strata. The latter assemblage is found in the Late Jurassic strata of the Toutunhe Formation, the Caishiling Formation, the upper section of Yaojie Formation to the Honggou Formation, the Zhiluo Formation and the Anding Formation, and the Ma'ao Formation and the Dongmengcun Formation (Deng et al., 2003).

Arguniella-*Sphaerium*-*Mengyinaia* is a representative assemblage of Early Cretaceous bivalves; however, with the decline of the *Ferganoconcha*, *Arguniella* have appeared in the Tiaojishan Formation (Huang, 2015, 2016).

According to Deng et al. (2003), the Jurassic bivalves of China have the following characteristic assemblages: (1) *Waagenoperna* beds, located in Member 4 of the Badaowan Formation in the Junggar Basin, are an early Early Jurassic assemblages, which also are found in the Paijiachong Member of the Guanyintan Formation in Hunan Province (Sha et al., 2016). (2) *Ferganoconcha* beds, which are located in the Dameigou Formation, Sangonghe Formation, and Fuxian Formation, developed in the late Early Jurassic. (3) *Pseudocardinia*-*Qiyangia* assemblage represents a dry-hot climate, and *Pseudocardinia* was a prosperous type in late Late Jurassic to Middle Jurassic in South China. (4) The *Lamprotula cremeri* and *Lamprotula guangyuanensis* assemblages date to the Middle-Late Jurassic of the Sichuan Basin. (5) The *Psilunio suni*-*Pseudocardinia* assemblage was found at the Anding Formation and the top of Wangjiashan Formation to the Kushuixia Formation and is dated to the late Late Jurassic.

5.4 Plants

Jurassic flora in China are prosperous. Fossil plants are the most common fossils in the Jurassic strata and are widely used to compare the continental Jurassic strata of China. In the Early-Middle Jurassic, coal-bearing strata were widely developed in China, and there were a large number of plant fossils. The compressed plant fossils of the Late Jurassic were relatively scarce, but abundant wood fossils were preserved. The Jurassic strata of China had two major groups of plants: the *Neocalamites*-*Cladophlebis* flora of the Early Jurassic and the *Coniopteris*-*Phoenicopsis* flora of the Middle-Late Jurassic.

According to Deng et al. (2003), *Neocalamites*-*Cladophlebis* flora can be divided into three assemblages: the lower assemblage is the *Zamites* bed, primarily composed of ferns and sphenopsids, and cycads are common, which developed in Member 1 of the Xiaomeigou Formation and in the lower section of the Badaowan Formation; the middle assemblage is the *Cladophlebis* bed, featuring the typical Jurassic fossil plant of *Coniopteris*, which developed in Member 2 of the Xiaomeigou Formation and the upper section of the Badaowan Formation; the upper assemblage is the *Hausmannia* bed, which developed in Member 3 of the Xiaomeigou Formation to the lower section of Dameigou Formation, the lower section of the Sangonghe Formation, the Tandonggou Formation, the Wudanggou Formation, the Fuxian Formation, and the Yongdingzhuang Formation The *Coniopteris*-*Phoenicopsis* flora is also divided into three assemblages: the lower assemblage is *Coniopteris hymenophylloides*-*Baiera*, where the true ferns predominate, the dicksoniaceae is developed, and the ginkgo is abundant, and where *C. hymenophylloides*, *C. tatungensis*, *Eboracia lobifolia* (CCE) coexist; the middle assemblage is *Coniopteris hymenophylloides*-*Anomozamites thomasi*, where CCE also coexist and *A. thomasi* and *Nilssoniopteris vittata* prosper; the upper assemblage is *Coniopteris hymenophylloides*-*Brachyphyllum*, which appeared in the upper part of the Toutunhe Formation Due to differences in elevation and climate in different regions, fossil plants in different strata have different vertical distributions, and the stratigraphic division of the lower-middle assemblages of the *Coniopteris*-*Phoenicopsis* flora is somewhat confusing. Two assemblages represent the flora of the Middle Jurassic to the early Late Jurassic, which correspond in age to the upper section of the Sangonghe Formation-Xishanyao Formation, the Yaopo Formation-Longmen Formation, the Beipiao Formation-Haifanggou Formation, Datong Formation-Yungang Formation, the upper section of the Fuxian Formation-Yan'an Formation, and the Yima Formation, which are similar to the Yorkshire flora.

In the Yaopo Formation (Lower Yaopo Member and Upper Yaopo Member) and the Longmen Formation of West Beijing, fossil plant assemblages developed with inherited features and disparate contents, namely Mentougou flora. No common new forms have appeared in the Upper Yaopo Member and the Longmen Formation (Chen et al., 1984). The development trend of the Mentougou flora shows a decline of ginkgos, which were prosperous groups of the Early Jurassic, and the development of true ferns and conifers, and in particular, conifers are very rich in the Zhaitang plant assemblage (Chen et al., 1984; Duan, 1989). A typical *Coniopteris*-*Phoenicopsis* assemblage developed in the Daohugou biota. *Baiera* developed in its early stage, and conifers dominated its late stage (Huang, 2016). This change in plant appearance not only is related to the evolution of the flora but also reflects the elevation of the terrain. For example, the prosperous conifers may suggest a relatively high elevation, which is represented by changes in the flora in the upper part of the Yaopo and Haifanggou Fms.

5.5 Pollen and spores

The Jurassic pollen and spores of China are extremely rich and well studied. Pollen and spore fossils often have the advantage of large numbers and wide distribution, and may be compared with that of the marine stata of Europe. It is one of the most important groups for stratigraphic division in the Jurassic (Figure 3).

The Jurassic pollen and spore assemblage in China is well represented in the Junggar Basin in Xinjiang (Lu, 1995; Deng et al., 2003, 2010, 2015). According to Deng et al. (2003), Jurassic pollen and spore assemblages in the Junggar

Basin are as follows:

(1) The Yongfeng Stage is represented by the *Osmundacidites*-*Cerebropollenites*-*Protoconiferus* assemblage, yielded in the Badaowan Formation, which contains a few Triassic forms and many Jurassic common forms with significance on age. (2) The Liuhuanggou Stage is represented by *Deltoidospora*-*Classopollis*-*Piceites* assemblage, yielded in the Sangonghe Formation, which corresponds in age to the Fuxian Formation, the lower section of the Dameigou Formation, the Wudanggou Formation, the Yongdingzhuang Formation, and the Beipiao Formation Each area has local features. The pollen and spore assemblage of the Sangonghe Formation is dominated by the common forms of the Early and Middle Jurassic (Huang, 1993), and the upper assemblages have shown the characteristics of the Middle Jurassic (Lu, 1995). The pollen and spore assemblage in the upper section of the Fuxian Formation shows similar characteristics of the period from the late Early Jurassic to the Middle Jurassic (Geological Institute of Chinese Academy of Geological Sciences, 1980a). (3) The Shihezi Stage is represented by the *Cyathidites*-*Neoraistrickia*-*Piceaepollenites* assemblage, yielded in the Xishanyao Formation, which corresponds in age to the upper section of the Dameigou Formation, Yan'an Formation, Haifanggou Formation, Yima Formation, Fangzi Formation, and the lower section of Yuantongshan Formation in Hefei Basin. Some researchers have called it the *Cyathidites*-*Neoraistrisckia*-*Disacciatrileti* (CND) assemblage (Huang and Li, 2007). Schizosporis and Reticulatasporites also can be found in the Yan'an Formation, but normally they appear in the Lower Cretaceous in other regions (Institute of Geology, Chinese Academy of Geological Sciences, 1980a). (4) The Manas Stage is represented by *Classopollis*-*Concavissimisporites*-*Cyathidites* assemblage, yielded in the Toutunhe Formation, which corresponds in age to the Zhiluo Formation, the Wangjiashan Formation, and the Santai Formation Some researchers have called it the *Cyathidites*-*Disacciatrileti*-*Classopollis* (CDC) assemblage (Huang and Li, 2007). The Early Cretaceous common form of *Concavissimisporites* has more or less appeared in this assemblage (Yuan et al., 2003). (5) The late Late Jurassic to the early Early Cretaceous is represented by the *Classopollis*-*Callialasporites*-*Schizaeoisporites* assemblage, which is typical of the Tuchengzi Formation in northern Hebei Province. Early Cretaceous common forms, such as *Concavissimisporites* and *Schizaeoisporites,* also have been found in the Anding Formation (Zhang, 1989).

The pollen and spores from the Tuchengzi Formation also can be referred to as the *Quadraculina*-*Classopollis* assemblage (Wang et al., 2004), but more often, they reflect the appearance of Member 1 of Tuchengzi Formation, which is similar to that of the Anding Formation (Geological Institute of the Chinese Academy of Geological Sciences, 1980a). A high concentration of *Classopollis* is found in the Tuchengzi Formation, which accounts for 57–82.6% of the Beipiao area and up to 91% of the Xuanhua area (Zhang, 1989; Wang et al., 2004). A decreasing upward trend is evident in the Tuchengzi Formation, where the concentration of *Classopollis* is 19.83% at the lower part of Member 3 but only 0.96% at the top layers of this formation (Lin et al., 2016). The late Jurassic strata in the Northern Hemisphere are usually rich in *Classopollis*, which often reach 40–90% concentration. A sharp reduction in these pollens occurred near the Jurassic-Cretaceous boundary, reflecting global climate change (Institute of Geology, Chinese Academy of Geological Sciences, 1980a).

The appearance of *Cicatricosisporites* generally is considered to be a sign of entering the Cretaceous period (Deng et al., 2015). It first appeared in the Tuchengzi Formation in the Yanliao Basin and the Anding Formation in the Ordos Basin (Geological Institute of the Chinese Academy of Geological Sciences, 1980a; Zhang, 1989; Wang et al., 2004). The pollen and spore assemblage of the Anding Formation shows a different appearance of the flora from the underlying strata (Yuan et al., 2003; Institute of Geology, Chinese Academy of Geological Sciences, 1980a). The assemblage is dominated by the Late Jurassic-Early Cretaceous common forms (Cai et al., 2010). A variety of *Concavissimisporites* occurred in the Anding Formation, including *C. variverrucatus*, common in the Early Cretaceous, and other early Cretaceous common forms, such as *Cicatricosisporites* and *Trilobosporites* (Geological Institute of Chinese Academy of Geological Sciences, 1980a), but the exact layer is unclear. The occurrence of *Cicatricosisporites* not only appeared in the Tuchengzi Formation in northern Hebei but also appeared in Member 1 of the Tuchengzi Formation at the Jing-Yang Basin of western Liaoning. The latter has a higher concentration of *Cicatricosisporites* (9.38%) and a lower concentration of *Rugubivesiculit*es (2.08%), but they did not appear in the lower part of this outcrop (Wang et al., 2004). This pollen and spore assemblage indicates the approximate bottom of the Cretaceous. The typical Early Cretaceous pollen and spores, such as *Cicatricosisporites*, *Lygodioisporites*, and *Rugubivesiculites*, can be found in Member 3 of the Tuchengzi Formation but no angiosperm pollens are found, which indicate an early Early Cretaceous age. This pollen and spore assemblage is quite similar to that of the lower section of the Yixian Formation in the western part of Liaoning, indicating that there is no essential difference between these two flora (Lin et al., 2016). From the pollen and spore analysis, the Jurassic-Cretaceous boundary should cross the upper section of Member 1 of the Tuchengzi Formation and the upper section of the Anding Formation, and the corresponding strata.

5.6 Ammonites

Ammonites are standardized fossils used to divide the boundaries of the Jurassic system. The marine Jurassic strata developed in Tibet, and the ammonoid biostratigraphy has undergone systematic research. The present paper briefly introduces the marine Jurassic ammonoid biostratigraphy based on a summary by Sun et al. (2000).

The Jurassic ammonoid biostratigraphy in China follows. The Planorbis Zone in the lower part of the Lower Jurassic Hettangian, the Angulata Zone in the upper part of the Hettangian; four ammonite zones in Sinemurian, the Bucklandi Zone, the Semicostatum Zone, the Turneri-Obtusum Zone, and the Oxynotum-Raricostatum Zone (from the bottom to top); Pliensbachian with four ammonite assemblages, *Galaticeras-Coeloceras*, *Fuciniceras-Prodactylioceras*, *Bouleiceras-Catacoeloceras*, and *Dumortieria-Grammoceras-Polyplectus*; Toarcian with *Dumortieria-Grammoceras-Polyplectus* and *Bouleiceras-Catacoeloceras* assemblages; Middle Jurassic Aalenian with *Leioceras-Geyerina-Ludwigia* assemblages; Bajocian with *Euhoploceras* and *Wetchellia-Fontannesia* assemblages; Bathonian with *Siemiradzkia*, *Oxycerites*, *Neuqueniceras*, and *Homoeoplanulites* assemblages (Yin, 2005); Callovian with four assemblages (from bottom to top), *Macrocephalites-Choffatia*, *Grayiceras-Subkossimatia*, *Erymnoceras*, *Grossouira-Alligaticeras*; the Upper Jurassic Oxfordian with *Peltoceratoides* and *Mayates-Dhosaites-Peresphinctes* assemblages; Kimmeridgian with *Rasenia-Proresania* and *Katraliceras-Metagravisia* assemblages; and Tithonian with three assemblages, *Aulacosphinctoides-Gymnodiscoceras*, *Aulacosphinctes-Virgatosphinctes*, and *Berriasella Jacobi-Blanfordiceras acuticosta-Himalayites* (Figure 3).

6. Jurassic Yanshan Movement

The concept of the Yanshan Movement was formally proposed by Wong in 1927 on the basis of the geological phenomenon of West Beijing. The movement suggests that the Sinian to Mesozoic Chinese strata are integrated and that the first unconformity occurred below the Tiaojishan Formation, which covers different ancient rocks. Therefore, Wong suggested that a major tectonic event occurred before the Tiaojishan Formation (Wong, 1927). Later, he believed that the Yanshan Movement occurred between the Haifanggou and Beipiao Fms. in the Beipiao Basin. It was only the beginning of the movement (Wong, 1928). He then divided the Yanshan Movement into three stages: the unconformity under the Tiaojishan Formation was the Curtain A (i.e., start period), Curtain B was the Early Cretaceous (i.e., main period), and a volcanic period occurred between Curtain A and B (Wong, 1929).

The Yanshan Movement is the most far-reaching and overarching tectonic event since the Phanerozoic period in eastern China and its neighboring regions. The major tectonic lines in eastern China have changed from moving in an east-west direction to the north-east and north-north-east (Ren, 1989). The Yanshanian period is an important metallogenic period in China. About 80% of large- and medium-size metal deposits are attributed to this period (Chen et al., 2007). Dong et al. (2000) believed that the scope covered by the Yanshan Movement and its global impact far exceeds the Yanshan area in eastern China. Many scholars have developed different schemes for the stage division of the Yanshan Movement. Although arguments persist as to Curtain A, general consensus has been reached regarding the fact that Curtain B is represented by an unconformity between the Tuchengzi and Zhangjiakou Formation-Yixian Formation in the Yanliao region with an age of about 136–135 Ma.

The Yanshan Movement tectonic phase refers to the interface beneath the Tiaojishan Formation proposed by Wong in 1927, but the commonly used Yanshan Movement is a term generally used to describe the Yanshanian orogeny. Xie (1937) considered that the contact between the Tiaojishan and Jiulongshan Fms. often was integrated, whereas the Jiulongshan Formation lay on top of the older truncated strata. Therefore, the Yanshan Movement should be located beneath the Jiulongshan Formation Huang (1954, 1960) noted that the Jiulongshan Formation and the Tiaojishan Formation are, in fact, phase transitions. Therefore, many researchers believe that Curtain A is located beneath the Tiaojishan Formation or the Tiaojishan-Jiulongshan Fms. Other researchers believe that Curtain A is located under a set of synorogenic conglomerates and that it is the bottom of the Longmen Formation in western Beijing, and the Haifanggou Formation in western Liaoning (Zhao, 1990; Zhang et al., 2013; Zhang, 2016). Huang (2015) considered that the Yanshan Movement, Curtain A, presented in 1927 in Jingxi Basin and in 1928 in Beipiao Basin, and that it represented a different interface. There are two unconformities beneath the Longmen Formation and the Jiulongshan-Tiaojishan Formation These two unconformities correspond in age to the bottom and top of the Haifanggou Formation or Longmen Formation, which can be called Curtain A1—that is, the start of the curtain—and Curtain A2—that is, the volcanic curtain (Figure 4). Curtain A1 is represented by a set of synorogenic conglomerates, which dates to about 168 Ma. Curtain A2 is located beneath a large set of volcanic rocks or pyroclastic rocks, and often is represented by an unconformity, which dates to about 161 Ma. Zhao et al. (2002) considered that the intracontinental deformation of the Yanshan Movement, Curtain A, began at the bottom of the Longmen/Haifanggou period and ended at the top of the Haifanggou period, with an age of 170–160 Ma. That means that the Yanshan Movement, Curtain A, transformed into a relatively long geological process, which began at a contraction that occurred at the end of the Yaopo/Beipiao period and ended before the large-scale magmatic activity of the Tiaojishan period.

The essence of the Yanshan Movement is the transition of the Ancient Asian Ocean structural system or the Ancient Tethys structural system to the active continental margin of the Ancient Pacific Ocean (Zhao et al., 1994). The continental collisional tectonic regime was transformed into an intracontinental deformation and an intracontinental orogeny was dominated by the western Pacific continental margin subduction structure (Dong et al., 2007). Since the Middle Jurassic, the north-south crust shortening, which is represented by the east-west Yanshan intraplate deformation belt, was replaced by the north-north-east case structure magmatism, which occurred after 135 Ma (Zhao et al., 2004a). The geodynamic mechanism of the Yanshan Movement has different interpretations: (1) The westward subduction of the Ancient Pacific Plate is the main reason for the destruction of the North China Craton, which corresponds in age to the two phases of the magmatic action of the Jurassic and the Cretaceous. The peak period of the destruction is from 125–120 Ma (Zhu et al., 2012). (2) The Jurassic Yanshan Movement was the result of the final collision between the Sino-Korean Block and the Siberia Block, and was not a product of the circum-Pacific tectonic magmatic zone (Zhao et al., 2002). (3) The Yanshan Movement is squeezing southward of the Siberia Plate, resulting in an alternation or superposition of the Mongolian-Okhotsk Ocean closure and the Pacific Plate westward subduction (Davis et al., 2001; Zheng and Dai, 2018; Liu S et al., 2017, 2018). (4) The Mesozoic tectonic transformation of North China is a large-scale uplift of the North China mantle, which was caused by the attack of the surrounding blocks (Zhai et al., 2004). (5) The Yanshan Movement is centered on the Sino-Korean plate and demonstrates "multidirectional convergence" from different northern, eastern, and southwestern plates to the East Asian continent. It formed the East Asian convergence structure system that is characterized by intracontinental subduction and intracontinental orogeny (Figure 1; Dong et al., 2000, 2007). Some researchers have suggested that the Tethys Ocean began to dive into the Asian continent in the Late Jurassic. The timing of the departure of the Indian Plate from the Gondwana and the counter-clockwise rotation of the Tethys Ocean synchronized with the splicing of the Lhasa Block and the Asian continent. (Dong et al., 2007). The impact of the Bangong-Nujiang suture zone and the collision between the Lhasa and Qiangtang Blocks mainly occurred in the Cretaceous (Zhang et al., 2017; Wei et al., 2017) or in the Late Jurassic at about 150 Ma (Li et al., 2017a). Therefore, the Tethys Ocean closure and the subduction of the Indian Plate to the Asian continent may not have had a significant impact on the Jurassic tectonic deformation in most parts of China.

Some researchers have divided a pre-orogenic curtain (203–175 Ma) before the Yanshan Movement, Curtain A (Deng et al., 2007). Some researchers have attributed the Early-Middle Jurassic tectonics to the Indosinian Movement. The strata or basin spread may have occurred in an east-west direction following up the impact of the Triassic continental collision, whereas the northeast-trending basin may have appeared in the Late Jurassic, representing the influence of the Yanshan Movement (Dong et al., 2007). Zhai et al. (2004) believed that a tectonic extruding period at the southern edge of North China occurred around 230–210 Ma, whereas a two-stage tectonic extrusion existed in the northern edge between 230–210 and 180–160 Ma. The early Early Jurassic deposits were missing in North China and north of South China, implying a significant uplift in East China during the Late Triassic. The molasses formation and volcanic rocks that developed in the northern edges of North China during the middle Early Jurassic both spread in an east-west direction. The relationship of this tectonic plate with the Yanshan Movement needs further study.

The Okhotsk Ocean is located in the northern part of the Mongolian-North China Block, dating from the Triassic to the end of the Jurassic. The Siberia Plate began a southward subduction and the Mongolia-Okhotsk Ocean closed at the Jurassic, which formed the Mongolian-Ohotsk structural belt extending from the Mongolian Hang'ai Mountains to the gulf of Okhotsk, which is more than 3000 km long (Zorin, 1999; Davis et al., 2001; Dong et al., 2008). The previously noted tectonics form a conjugate strike-slip fault system in the northern part of the Tianshan-Yanshan areas in China or Meso-Cenozoic circum-Siberian intracontinental tectonic system (Zhang et al., 2002; Dong et al., 2008). Therefore, given the subduction of the Siberia Plate from north to south, the Okhotsk Ocean closed from west to east, and a series of related geological actions occurred in the Jurassic strata of the northern part to China.

Molasse formation and medium-acid magmatism developed at the northern edge of North China Block during 168–164 Ma. This molasse formation, including the conglomerate of the Haifanggou, Longmen, and Wanbao Fms., created an unconformity in some areas with underlying strata. A volcanic clastic rock interlayer often developed in the middle and lower parts of the conglomerate, suggesting the beginning of volcanic activity. Tuffaceous gravel gradually increased in the upper conglomerate layers. The gravel usually is poorly sorted, its roundness is better in the inherited basins, and it is breccia in newer basins. Gravel comes primarily from ancient strata, and mainly includes granites, gneisses, quartzites, silicalites, carbonate rocks, and ancient volcanic rocks, reflecting deep denudation and suggesting a tectonic uplift before 168 Ma. There was an obvious contraction in the Yanliao region during the late Haifanggou period, when the mountain uplifted and the lake basin was destroyed and north-facing rivers developed. A regional unconformity below the Tiaojishan Formation formed at 161 Ma and was followed by large-scale magmatic activity. The disconformities between Santai and Fangzi Fms. in Shandong, Dongmengcun and Yima Fms., and the Ma'ao and Yangshuzhuang Fms. in the Henan, Zhougongshan and Yuantongshan Fms. of the Hefei Basin (Xiu et al., 2003) correspond in age to the unconformity beneath the Tiaojishan Formation.

A large Jurassic nappe structure developed along the border between China and Mongolia in the northern part of China, and its strike and age are basically the same as the closure of the Mongolia-Okhotsk Ocean (Zheng et al., 1990; Zheng et al., 1998; Zhao et al., 2002). The Late Jurassic strata of the Yanshan-Yinshan region experienced a strong overburden-uplift event in a tectonic setting from north to south and developed large-scale thick clastic accumulations in the east-west large-scale depression belt, suggesting that the northern side of the parallel area experienced a large-scale uplift (He et al., 1998). Therefore, the Middle-Late Jurassic structural deformations generally developed in northern China, which are related to the closure and collisional orogeny of the Mongolia-Okhotsk Ocean. The thick layer conglomerate sometimes is distributed on the bottom of the Yan'an Formation in the Ordos Basin (Yuan et al., 2003), which probably corresponds in age to the Yanshan Movement, Curtain A1. The disconformity between the Zhiluo and Yan'an Fms. (Yuan et al., 2003) should correspond to Curtain A2. The Middle-Late Jurassic nappe structure and thrust fault developed from north to south along the northern edge of the Ordos Basin. The Shiguai Basin developed around the Middle Jurassic strong fold deformation. The Precambrian strata overlaid on the Jurassic rocks and the compressed direction was near the north-south direction (Zhang Y et al., 2007).

In the northwest region, including the Xishanyao Formation in the Junggar Basin, a thick-bottom conglomerate sometimes developed, and the gravel's sorting degree and roundness were poor. The composition of gravel is dominated by quartzite, siliceous rock, and metamorphic rock (Deng et al., 2010), which suggests that the crust was probably lifted and denuded during the Yanshan Movement, Curtain A1. Although volcanic rocks or tuffs have not been found in the Xishanyao Formation, this period of volcanic activity is likely to exist. For example, the zircon U-Pb age (164.6±1.4 Ma) of the Qigu Formation (Wang and Gao, 2012) may well include captured zircons from the Xishanyao period. There is an unconformity between the Toutunhe and Xishanyao Fms. (Eberth et al., 2001; Liu and Li, 2001; Deng et al., 2010). The age of the bottom of the Toutunhe Formation is approximately 161.2 Ma (Fang et al., 2015), which coincides with the age of the unconformity beneath the Tiaojishan Formation in the Yanliao region. The Okhotsk Ocean presents a trumpet shape that opens to the east, and its impact of closure on the western region may be smaller although it may have occurred earlier. In addition, only one unconformity is evident before the Cretaceous in the Karatuo area of Kazakhstan, which is located near the Middle-Late Jurassic boundary. That is, the Karabastau Formation is overlaid on top of different Paleozoic rocks, and the most recent strata are from the late Early Jurassic to the Middle Jurassic (Doludenko and Orlovskaya, 1976). This feature resembles that of the Tiaojishan Formation in Beijing, whereas the Karabastau Formation and the Tiaojishan Formation can be fully mapped in age (Huang, 2015). Therefore, this unconformity also may be related to the southward subduction of the Siberian Plate.

The closure and collisional orogeny of the sea basin in the eastern section of the Mongolia-Okhotsk tectonic belt occurred primarily during the Middle-Late Jurassic and formed a large-scale thrusting structure toward the southward thrust (Zonenshain et al., 1990; Khain, 1994). In the Xingan Mountains area of northeastern China, a molasse formation developed at the bottom of the Wanbao Formation, which is covered on an unconformity on the Hongqi Formation The Wanbao Formation yielded two stages of zircons, 165 Ma and 162 Ma, which corresponded in age to the early and late volcanic activities of the Haifanggou Formation The magma activity in the Wanbao Formation is closely related to the evolution of the Mongolia-Okhotsk suture zone (Zhang et al., 2018).

The middle Late Mesozoic strata in western Liaoning were strongly transformed by the Yanshan Movement, Curtain A, forming an unconformity and strong magmatic activity. The strata were integrated and the volcanic activity was weak, however, in the eastern part of Liaoning during this period. Such geological appearance confirmed that Yanshan Movement, Curtain A, was compressed in a northwest direction in the Yanliao region and that the strike-slip movement of the Tanlu fault reduced stress. Therefore, the Yanshan Movement, Curtain A, barely affected the region east of the Tanlu fault. Such characteristics also indicated that the westward subduction of the Ancient-Pacific Plate did not occur or had a weak influence in the Middle Jurassic to the early Late Jurassic. The area east of the Tanlu fault generally lacked stratigraphy from the late Late Jurassic to the early Early Cretaceous (before the Yanshan Movement, Curtain B), suggesting that the Ancient Pacific Plate subducted westward and caused an uplift and sedimentary discontinuities at that time. Similarly, this influence is weak in the area west of the Tanlu fault. Therefore, the southward subduction of the Siberia Plate and the subduction of the Ancient Pacific Plate moved westward, resulting in the conversion of Yanshan Movement, Curtain A to Curtain B. A shifting and gradual process took place at approximately 145 to 140 Ma.

Therefore, the Jurassic Yanshan Movement may have been subducted by southward subduction of the Siberia Plate and the closure of the Mongolia-Okhotsk Ocean, affecting vast areas in the northern part of China, including the northwest and northeast, and gradually weakening areas from north to south. The closing of the Mongolia-Okhotsk Ocean occurred during the Middle-Late Jurassic, although paleomagnetism studies have indicated that it was completely closed by the Early Cretaceous (ca. 130 Ma) (Zhao et al., 1990; Enkin et al., 1992; Gilder and Courtillot, 1997). The Middle Jurassic radiolarian flysch accretion wedge found in the continental margins or Japan or East Asian confirms that the Ancient Pacific Plate dives westward not earlier than the Middle Jurassic (Mizutani et al., 1989; Maruyama et al., 1989, 1997; Isozaki, 1997). The subduction of the Ancient Pacific Plate westward during the Cretaceous period is represented in particular by the Yanshan Movement, Curtain B. It became the dominant factor in the structural deformation of the eastern part of the ancient Asian continent and the destruction of the North China Craton. Therefore, the Yanshan Movement, Curtain B has a strong and extensive influence in eastern China, which gradually weakens from east to west. Therefore, the present paper believes that the Jurassic Yanshan Movement was controlled mainly by the southward subduction of the Siberia Plate, whereas the Ancient Pacific Plate westward subduction had a weak influence, and the Cretaceous Yanshan Movement was controlled by the westward subduction of the Ancient Pacific Plate.

7. Chinese Mesozoic Eastern Plateau and High Mountains

Ren et al. (1990) first proposed the Chinese Mesozoic Eastern Plateau. Deng et al. (1996, 2000) believed that the eastern part of China, which is represented by the Yanliao region, had a crust thickness of about 60–70 km in the late Mesozoic, similar to the recent Qinghai-Tibetan Plateau, and that it constitutes the magnificent Mesozoic plateau-mountain system (Niu et al., 2004). The extensive discovery of adakite is considered to provide important evidence for the existence of the Chinese Mesozoic Eastern Plateau (Zhang et al., 2001a, 2001b). Differences in the understanding of the origin and significance of these rocks, however, may have no relationship with the thickened crust (Ge et al., 2002; Ma et al., 2015, 2016).

Other researchers believe that the plateau in eastern China began to rise during the Indosinian period and rose to a height of 5000 to 6000 meters before the Late Jurassic lithosphere was extremely thinned (Dong et al., 2000). Researchers also believe that the Triassic-Early Jurassic had a significant east-western mountain range in northern Hebei, Liaoning, and southern Inner Mongolia. The volcanic eruption of the Tiaojishan period marked the rapid rise of the plateau. The survival time was 165–125 Ma. The northern edge of the eastern plateau may have a significant east-western extension of the mountains that is comparable to the modern Himalayas in the Early Cretaceous (Zhang et al., 2008).

In the Middle-Late Jurassic, the Daohugou biota developed in the Yanliao area as an early representative assemblage of the Yanliao biota. At the late stage of the Haigougou period, the terrain continuously elevated, the lake system was destroyed, and large-scale volcanic activity took place during the Tiaojishan period. Then, the Yanliao biota notably transitioned and developed into an inherited Linglongta biota, representing the late assemblage of the Yanliao biota (Huang, 2015, 2016). For example, the same groups of fossil insects of the Junggar and Ordos Basins have been discovered in the Yanliao biota. In the Middle-Late Jurassic, there are two important exceptionally preserved biotas in the close latitudes of northwestern China: the Shar Teg biota in southwestern Mongolia and the Karatau biota in Kazakhstan (Szwedo and Żyła, 2009; Ponomarenko et al., 2014). Their age ranges from the late Middle Jurassic to the Late Jurassic, which explains the generalized Yanliao biota. The biological appearance between these three biotas is similar, and there are a large number of common genus and even similar species. This similarity supports the wide range of biological exchanges and similar climatic conditions that occurred between the Yanliao area and Central Asia at that time. It does not support the hypothesis that a significant plateau existed in the Yanliao region during the Middle-Late Jurassic.

The transition from the Yanliao biota to the Jehol biota occurred in approximately the Tuchengzi period, and the evolution of different groups is different (Huang, 2015). The Early Cretaceous Jehol biota was distributed widely in the Xingan Mountains, Northwest China, East China, and eastern South China, with the Yanliao region as its center. Therefore, no matter how the northern boundary of the so-called Eastern Plateau (Zhang Q et al., 2007) moves, it cannot be denied that an extensive biological exchange occurred in North China (from east to west) and East China (from north to south) in the Early Cretaceous. Therefore, no sufficient evidence supports the existence of a significant plateau or east-western mountain range in eastern China during the Jehol biota period. The Early Cretaceous deposits of ice rafts and glacial debris found in northern China (Wang et al., 1996; Cheng et al., 2002) are not contradictory with low elevations. More evidence suggests that the temperature during the Jehol biota period was relatively cold (Amiot et al., 2011; Xu X et al., 2012).

Some researchers have theorized that there is no high mountain nearby the Daohugou region because the snakefly has not been discovered in this area (Tan and Ren, 2002). Snakeflies are in fact common in Daogou (Huang, 2016). Modern snakeflies generally live in cold forests and in low latitudes live in mountains above 1000 m (Grimaldi and Engel, 2005). It is generally believed that the climate of Daohugou biota was warm and humid. Therefore, the appearance of a large number of snakeflies suggests the existence of mountain ranges. The snakeflies of the Jehol biota are common, suggesting a cool climate and possibly a mountainous environment. A special type of cicada discovered in Daohugou provides additional evidence of high altitude (Liu et al., 2016). Its modern counterparts live close to high altitude in Tasmania. In the summer, such cicada live at about 1600 m, and in the winter, it lives at about 800 m (Evans, 1941). The plants of Daohugou biota are similar to that of the Xishanyao and Yan'an Fms. The conifers and mosses were prosperous is the upper layers, which also confirmed the mountain environment in the late stage of the Daohugou biota. Deng et al. (2017) believe that the temperature in the Jurassic is warmer than in modern times, and the location of the Yanliao region has not changed since the Jurassic to the recent era, so the paleoecological environment of Daohugou biota may be slightly higher than modern comparable habitats, reaching 2000 m.

In addition, the lack of Middle-Late Mesozoic zircons in the Ordos Basin, for example, the age of the youngest detrital zircons in the Yan'an Formation, was concentrated in the Early-Middle Triassic (Zhao et al., 2015; Guo et al., 2017), and the youngest zircons (165 Ma) appear in the Zhiluo Formation (Chen et al., 2017). This age may confirm the volcanic activities and topographic uplift of the middle-late Middle Jurassic in the northern edge of North China. That is, the 165 Ma zircons are common in the early stage of the Haifanggou period, and they began to erode and moved westward after the uplift of the late Haifanggou period.

The eastern region of China (the eastern part of North China and the northern parts of South China) had a significant uplift during the Late Triassic. A significant mountain-plateau system formed north of the ancient Qinling-ancient Dabie Mountains, and thus the early Early Jurassic deposition was generally absent. The highest area is in Shandong Province and continued long-lasting denudation, thus lacking the Late Triassic-Early Jurassic strata. The marginal regions, such as the Yanliao region and the region along the Yangtze River, are at a relatively lower altitude, with development of the Late Triassic and late Early Jurassic deposition. This extensive uplift may be related to the southeastward subduction of the North China Block to the South China Block during the Late Triassic to Early Jurassic (Li et al., 2017b). Both the southern and northern edges of the eastern plateau of the middle Early Jurassic was strongly denuded to form a molasse formation, which is represented by a quartz conglomerate at the bottom of Xiangshan Group and the Fanghushan Formation at the southern edge and by a limestone conglomerate at the bottom of the Xingshikou Formation Magmatic activity then developed that corresponds in age to the Xinglonggou and Nandailing Fms., and tuff interlayers of the Yongdingzhuang Formation in the Ningwu-Jingle Basin of Shanxi Province suggest an age of 179.2±0.79 Ma (Li et al., 2015). This bimodal volcanic rock is represented by basalt and andesite and dates to about 179–173 Ma. Above the volcanic rocks, coal-bearing strata are developed, specifically in the Beipiao Formation, the Yaopo Formation and the Datong Formation North China, especially the northern edge of the North China Block, compressed and uplifted, which was affected by the southward subduction of the Siberian Plate and the closure of the Mongolian-Ochowsk Ocean from 170 to 168 Ma. Severe denudation occurred along the northern edge of the North China Block during 168–164 Ma and developed a molasse formation. Yanliao region compressed and uplifted again from 163 to 161 Ma, which was followed by large-scale volcanic activity during the Tiaojishan period. The conglomerate in the middle and lower parts of the Tuchengzi Formation has shown the characteristics of molasse formation, which indicate a depositional response during the intracontinental orogenic process (Sun et al., 2007). A strong compressing activity occurred at the end of the Tuchengzi period, namely the Yanshan Movement, Curtain B. Thus, the northern North China and northeastern China basins shifted toward the extensional background (Meng et al., 2002; Liu et al., 2004).

In summary, the early Early Jurassic of the Yanliao region in China had a mountainous-plateau environment. During the middle Early Jurassic, intense erosion occurred, forming a molasse formation. Coal-bearing strata developed in the late Early Jurassic to early Middle Jurassic. The Yanshanian mountain-basin system formed after it was uplifted and strongly denuded during 170–168 Ma. The Yanliao region extruded and uplifted again during 163–161 Ma. A dry low-altitude plateau formed after the denudation from the Late Jurassic to the beginning of the Early Cretaceous. It extruded and uplifted again before 136 Ma and then formed rift basins in a wide area. These tectonics correspond in age to the uplift of the Mentougou flora in its late stage, the development of the Daohugou biota habitat from low to high, the mountainous environment of the Linglongta biota, the low-altitude plateau of the Tuchengzi period, and vast mountains during the Jehol biota period. In general, however, the elevation of the Yanliao region from the beginning of the Jurassic to the Early Cretaceous gradually decreased, although there were three significant contractions and uplifts (Figure 4).

8. Yanliao Biota

The Yanliao biota is the most important terrestrial biota in the Jurassic of China. It contains a large number of exceptional preserved fossils, including insects, crustaceans, spiders, millipedes, mollusks, fishes, salamanders, lizards, pterosaurs, dinosaurs, mammals, plants, pollen and spores, and fungi (Huang, 2016). The term Yanliao biota originates from the Yanliao entomofauna established by Hong (1983), which refers to the Haifanggou Formation and correlated strata with insect fossils. The Yanliao biota is distributed north of the Yellow River and west of Xinjiang to Central Asia. The entomofauna is characterized by the fossil insects of the Haifanggou Formation at Beipiao, West Liaoning, and the Jiulongshan Formation (i.e., Longmen Formation) at Zhouyingzi in Luanping County, North Hebei. Huang (2015) divided the Yanliao biota into an early assemblage represented by the Daohugou biota (Shihezi Stage) and a late assemblage represented by the Linglongta biota (Manas Stage). Some representatives have appeared in the bottom conglomerate of the Daohugou bed and the lower plant assemblage inherited from the Yaopo Formation. Therefore, the origin of the Yanliao biota can be traced back to more ancient strata (Huang et al., 2015).

The famous flora of *Coniopteris-Phoenicopsis* developed in the Middle Jurassic in China. It germinated in the middle Early Jurassic (middle-late Yongfeng Stage to early Liuhuanggou Stage), and during the early Middle Jurassic (late Liuhuanggou Stage), it began to take shape. The flora became prosperous in the middle-late Middle Jurassic to the beginning of the Late Jurassic (Shihezi Stage), further developed in the early Late Jurassic (Manas Stage), and obviously declined in the middle Late Jurassic (ca. 155 Ma) followed by the advent of drought events in the northern hemisphere. The coevolution and correlation of flora and animals play a decisive role in the evolutionary history of life. Therefore, the development of *Coniopteris-Phoenicopsis* flora was accompanied by the initiation, development, prosperity, proliferation, and decline of the Yanliao biota. Moreover, the flora is also an important part of the Yanliao biota. Therefore, the early representatives of the Yanliao biota appeared before the Middle Jurassic. The biota developed during the early Middle Jurassic and already exhibited the typical characteristics of the ecosystem. A highly diverse ecosystem (i.e., Daohugou biota) occurred after the Yanshan Movement, Curtain A1 (ca. 168 Ma) with changes in the local environment and the appearance of new niches. The biota changed dramatically and migrated westward near the Yanshan Movement, Curtain A2 (ca. 161 Ma), with large-scale volcanic activity and tectonics, and formed a local successive ecosystem (i.e., the Linglongta biota). With the advent of an arid climate, the Yanliao biota rapidly declined in the middle Late Jurassic (Figure 4), and some of the relict groups migrated southward. The delicate volcanic ash produced by the frequent volcanic activity in the Haifanggou and the Tiaojishan periods in the Yanliao region is a key factor in the exceptional preservation of the biota.

The Yanliao biota is located in northern China with a central area including northern Hebei, western Liaoning, and southeastern Inner Mongolia. The major features of the environment inclue the mountain, lake, and forest in the orogenic belt. It spreads southward to the ancient Kunlun Mountains-ancient Qinling Mountains-ancient Dabie Mountains, for example, the Hanshan biota (Cao, 1985; Lin, 1985; Shen, 1985; Lu et al., 1985), even reached the eastern part of the ancient Dabie Mountains along the coastal areas of Zhejiang and Fujian provinces. The eastern range of the Yanliao biota reaches to the ancient Pacific Ocean and extends northward to the coast of the Okhotsk Ocean. From the current fossil records, we can see that the distribution of the *Triglypta ziliujingensis* Zone of conchostracans reaches at least the boarder of Mongolia, China, and Russia as well as the southeastern area of Mongolia (Bao et al., 2011; Li G et al., 2014). The Yanliao biota reaches westward at least to Kazakhstan and is characterized by the late assemblage, such as the Karatau biota. The generalized Yanliao biota may contain the Shar Teg biota of the Republic of Mongolia and the Karatau biota of Kazakhstan. According to an analysis of the relationship between the biota and the unconformity of the Yanshan Movement, the Shar Teg biota is probably correlated with the Daohugou biota and the Karatau biota is corralled with the Linglongta biota (Huang, 2015, 2016). The age of the core fossil layers of the Daohugou biota and the Linglongta biota is less than 5 Ma, but the same animal species has not been discovered to date because of the violent tectonic movement and fierce volcanic eruptions. The Shar Teg biota and the Karatau biota share many identical insects, reflecting the reproduction of the biota in a relatively calm geological environment.

The assemblages of the Yanliao biota originated from three parts: (1) an indigenous type originated in North China; (2) the eastward migration of Eraly Jurassic biota of Europe; and (3) a biological fusion occurred after the collision between North China and South China blocks. Many related insect species from the European Eraly Jurassic are found in the Daohugou biota (Huang, 2015), reflecting the eastward expansion of the European Early Jurassic biota after the plates united, and some residues in Central Asia are represented by several early Middle Jurassic fossil localities. The Hanshan biota represent the fusion of the biotic province in North China and South China. For example, conchostracans include both northern triglyptids and advanced southern types, which is indicative of the southern margins of the Yanliao biota.

The expansion and migration of the Yanliao biota is extremely important for the development of the Late Mesozoic biota in East Asia. Until the end of Early Cretaceous (Late Albian), Burmese amber was recorded for a number of endemic insect groups in the Daohugou biota, but they were never found in the Jehol biota and represent relics of the Yanliao biota (Huang, 2015).

9. Problems and future directions

The distribution of Jurassic marine strata of China is limited, but the biostratigraphy has been studied in depth, including ammonites, brachiopods, and bivalves. Although this has not provided the necessary conditions to establish the stages, the ammonite sequence in the Qinghai-Tibet region does basically compare with that of the European standard strata. Despite limited conditions, Chinese scholars have relentlessly conducted research on the Jurassic marine-terrestrial alternating stratigraphic paleontology. As of yet, we have not reached a systematic solution to connect the Jurassic marine-

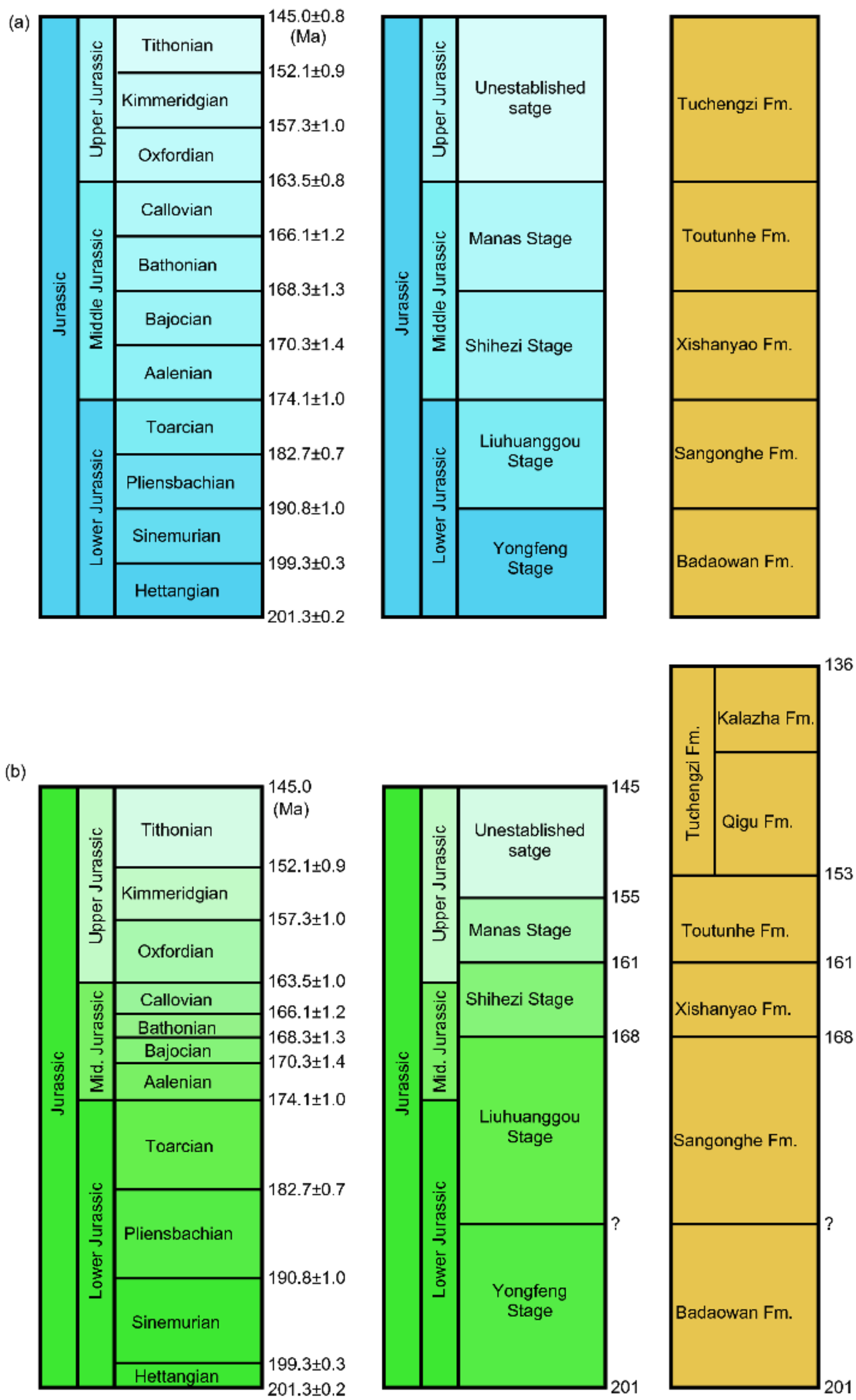

Figure 5 The comparison of the terrestrial stages from Chinese Stratigraphic Table (2014) (a) and that in the present paper (b).

terrestrial system in China. This system remains the key subject for future research that focuses on related strata, including Tibet, Heilongjiang, Yunnan, and Guangdong.

The terrestrial strata is the focus of Jurassic strata and biota in China, and the ability to correctly and accurately divide and compare the stratigraphy is the basis for conducting sedimentology, structural geology, geochemistry, and isotopic chronology. In the present paper, we proposed a new opinion regarding the Jurassic-Cretaceous boundary and analyzed the bottom age of the Fifth Stage of the Jurassic, the Manas Stage, and the Shihezi Stage. The bottom age of the Liuhuanggou Stage, however, remains unclear because we lack accurate marine-continental stratigraphic comparisons and isotopic geochronological data, and pollen and spore research is insufficient to solve the related problems. The early Early Jurassic sediments generally were absent in the central and eastern of China. Therefore, the in-depth study of the stratigraphic paleontology of the Jurassic basin with continuous sediments remains the key to solving problems such as those in the Xinjiang and Qinghai areas.

In contrast to the findings of the editorial committee of the "Chinese Stratigraphic Table" of the Chinese Stratigraphy Committee (2014), this paper made some critical improvements and increased the ranges of the Yongfeng and Liuhuanggou stages. We believe the top boundary of the Liuhuanggou Stage already has reached the middle Middle Jurassic. Moreover, the positions of the middle and upper Jurassic stages have significantly shifted upward. The unestablished Fifth Stage corresponds to the middle-late Late Jurassic (155–145 Ma), which is equivalent to the top of the Tiaojishan Formation to the lower part of the Tuchengzi Formation in the western Liaoning region (Figure 5). This finding suggests that the fifth stage should be established in the Qigu Formation in the Junggar Basin, Xinjiang, to ensure the continuity of these Jurassic terrestrial stages in China.

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