

New progress on the correlation of Chinese terrestrial Permo-Triassic strata (Postprint)

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Abstract

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Full Text

Preamble

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New progress on the correlation of Chinese terrestrial Permo-Triassic strata

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Summary

This paper reviews recent works on the age of Chinese terrestrial Permo-Triassic strata, mainly based on isotopic dating and tetrapod correlation. For stage-level division of Permo-Triassic strata, the best method is Thermal Ionization Mass Spectrometry (TIMS), while Secondary Ion Mass Spectroscopy (SIMS) can be used for many cases. However, the most popular Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS), which has nearly 4% error (>8 Myr), is of little use (Li et al., 2015).

The ages of major terrestrial strata are discussed for the Junggar Basin and Turfan-Hami Basin, the North Qilian area, the North China area, and the South China area.

Junggar Basin and Turfan-Hami Basin: Yang et al. (2010) published dating results that significantly changed the correlation of Permian strata in this area. The base of the Permian lies within the Daheyan Formation. The Lucaogou Formation is moved from Guadalupian or Lopingian to Cisuralian in age. The Hongyanchi Formation is Artinskian in age. There is a big time gap between the Hongyanchi and Quanzijie formations. The Quanzijie Formation possibly belongs to the Capitanian, although Lucas (2001, 2017) insisted on a younger age. The Wutonggou Formation is Wuchiapingian in age. The transition from Permian to Triassic falls within the Guodikeng Formation based on the study of various fossil groups, but there is no clear-cut position for the P-T boundary right now. The age of the Karamay Formation is unsure. The base of the Jurassic lies at the top of the Haojiagou Formation (Lu and Deng, 2005) or within it (Huang, 2006).

North Qilian area: The Qingtoushan Formation belongs to the Guadalupian (Roadian or Wordian) in age based on the Dashankou Fauna (Rubidge, 2005; Liu et al., 2009; Lucas, 2017). So, the underlying Yaogou Formation should be early-middle Guadalupian or late Cisuralian. The dicynodont from the top of the Sunan Formation suggested a late Lopingian age (Li et al., 2000; Kammerer et al., 2011), while the flora from the lower part suggested Wuchiapingian (Sun K Q et al., 2010). There could be little Capitanian deposits in this area.

North China area: The typical Permian and Triassic section in this area includes the Taiyuan, Shanxi (Shansi), Xiashihezi (Lower Shihhotse), Shangshihezi (Upper Shihhotse), Sunjiagou, Liujiagou, Heshanggou, Ermaying, Tongchuan, Yongping, and Wayaopu formations.

The Taiyuan Formation includes both marine and terrestrial facies, and the base of the Permian lies within this formation. Its upper portion is Artinskian in age based on conodont *Sweetognathus whitei* (Mei and Henderson, 2001; Wang and Qi, 2003). The Shanxi Formation is also Artinskian in age based on miospores (Liu et al., 2015). The Xiashihezi Formation is correlated to Kungurian to Wordian. The upper part of the Shangshihezi Formation was correlated with the *Cistecephalus* Assemblage Zone of South Africa, and it is estimated earlier

than 255 Ma (Rubidge et al., 2013; Liu J et al., 2014). The P-T boundary is traditionally put between the Sunjiagou Formation and the Liujiagou Formation, or could lie within the Sunjiagou Formation (Yin and Lin, 1979). However, the latter hypothesis is not supported by the pareiasaur occurrence (Gao, 1983).

Our recent work indicated the base of the Anisian (Lower/Middle Triassic boundary) could lie within the Heshanggou Formation (Liu et al., 2018), as suggested by Rubidge (2005). The base of the Ladinian roughly equals the base of the Tongchuan Formation, and the base of the Carnian lies above the top of the Tongchuan Formation (Wang et al., 2014).

South China area: The terrestrial deposits in this area began from the Xuanwei Formation (Lopingian) in western Guizhou and east Yunnan (east margin of the Kangdian High). The Kayitou Formation is a transitional unit both in age and facies. The P-T boundary lies within the Kayitou Formation for most if not all sections, and the Dongchuan Formation is Induan in age (Chu et al., 2016, 2017; Zhang H et al., 2016).

The Badong Formation has some terrestrial members such as Member II, which produced terrestrial tetrapod *Lotosaurus* and *Yuanansuchus* (Zhang, 1975; Liu and Wang, 2005; Liu, 2016). The Badong Formation is generally regarded as Middle Triassic in age, and there is no real advance on this.

The Xujiahe Formation produced diverse fossil plants and the oldest dinosaur footprints in China. It was dated as Rhaetian by the marine bivalve from the underlying Xiaotangzi Formation. This result was confirmed by astronomical tuning and magnetostratigraphy (Li et al., 2017).

Abstract

This paper summarizes new understanding of the chronology of terrestrial Permian and Triassic strata from the past decade, based primarily on isotopic dating and tetrapod fossil correlation, focusing on new correlation schemes for the Junggar and Turfan-Hami basins of Xinjiang, the North Qilian area, and the North China stratigraphic region. Isotopic dating results from the Turfan-Hami Basin of Xinjiang confirm that the Hongyanchi Formation and underlying Lucaogou Formation belong to the Cisuralian Series, the Quanzijie Formation belongs to the Guadalupian Series, and only the Wutonggou and Guodikeng formations belong to the Lopingian Series. A substantial depositional hiatus exists between the Hongyanchi and Quanzijie formations, and another may exist between the Shaofanggou and Karamay formations. The age of *Urumqia* is essentially consistent with that of most Seymouriamorpha abroad, representing the oldest known Permian tetrapod fossil in China. Vertebrate fossil correlation indicates that the Qingtoushan Formation in the North Qilian area corresponds to the lower Guadalupian Series, while the Sunan Formation belongs to the Lopingian Series, with a possible depositional hiatus in between. The Upper and Lower Shihhotse formations in North China may both encompass long temporal spans; the Upper Shihhotse Formation extends into the upper Wuchiapingian

Stage. Based on pareiasaur fossils, the Sunjiagou Formation essentially belongs to the Permian System. An age of 243.5 Ma from the lower part of the second member of the Ermaying Formation supports a late Anisian age for this formation. The top of the Tongchuan Formation remains within the Ladinian Stage and does not extend into the Carnian Stage.

Keywords: Permian System, Triassic System, zircon U-Pb dating, stratigraphic correlation, tetrapod fossils

During the Permian and Triassic periods, China's basic pattern was "land in the north, sea in the south." The North China Block, Tarim Block, and northern Xinjiang fold belt in the north were dominated by terrestrial deposition, while the South China Block and Tibet Block in the south were dominated by shallow marine carbonate deposition (Jin et al., 2000). Typical terrestrial sedimentary basins include the Junggar, Turfan-Hami, and Ordos basins, which contain relatively continuous Permian and Triassic sequences, yield abundant fossils from various groups, and host oil, gas, and coal resources. These basins have been studied intensively and contain classic stratigraphic sections. Additionally, some smaller sedimentary basins also have well-preserved sequences. Through the work of generations of geologists over the past century, China has established preliminary divisions and correlation schemes for terrestrial Permian and Triassic strata (Jin et al., 2000; Yang et al., 2000).

In recent years, new stratigraphic correlation results have been published, including those based on isotopic dating data. These discoveries have advanced our understanding of stratigraphic chronology. This paper reviews currently employed zircon U-Pb dating methods and summarizes, primarily based on dating results, new understanding of the chronology of major Chinese terrestrial Permian and Triassic strata since 2000, while also identifying existing problems and possible directions for further work.

1 High-Precision Correlation Methods for Terrestrial Strata

Establishing a fine chronostratigraphic framework for terrestrial strata is a challenging scientific problem. The stages of the Permian and Triassic systems are all defined in marine strata, and terrestrial strata are generally difficult to correlate with marine strata. This causes the same chronostratigraphic units (e.g., Middle Triassic Series) to often be inconsistent with their defined meanings when applied to terrestrial strata. Marine-terrestrial correlation methods include: searching for coexisting fossils in marine and terrestrial strata, finding marine interbeds in terrestrial strata and using marine index fossils for correlation (e.g., the correlation between Permian tetrapod zones and marine fossil zones in Texas (Lucas et al., 2006)); using global climate changes to correlate marine and terrestrial strata (Krassilov and Karasev, 2009); and utilizing isotopic variation curves, magnetostratigraphy, and astronomical cyclostratigraphy (e.g., Zhang H et al., 2016; Li et al., 2017; Lucas, 2017). Of course, the most

direct method is through absolute age determination.

For stage-level correlation, dating must achieve certain precision. Currently, common geological dating methods for Permian and Triassic strata include the zircon U-Pb method and sanidine $^{40}\text{Ar}/^{39}\text{Ar}$ method. The zircon U-Pb method mainly includes Thermal Ionization Mass Spectrometry (TIMS), Secondary Ion Mass Spectrometry (SIMS), and Laser Ablation-Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS). The latter two methods have been widely applied due to their low cost and fast analysis speed. SIMS results have an error of about 1% (Schmitz and Kuiper, 2013), which translates to about 2–3 Myr for Permian and Triassic strata—sufficient to resolve some correlation problems. LA-ICP-MS has poor external reproducibility (accuracy) with errors reaching about 4% (Li et al., 2015), corresponding to about 8–12 Myr for Permian and Triassic strata, making it unsuitable for resolving stage-level or even series-level chronostratigraphic problems. TIMS precision can reach 0.1% for single crystals and 0.03% for weighted averages (Schmitz and Kuiper, 2013), yielding errors of less than 0.3 Myr and 0.1 Myr respectively for Permian and Triassic strata—sufficiently precise for most applications. Currently, the best method is Chemical Abrasion-TIMS (CA-TIMS) (Mattinson, 2005), which can overcome lead loss, though few laboratories are equipped to perform this technique. The $^{40}\text{Ar}/^{39}\text{Ar}$ method only measures relative ages and must be combined with other methods such as K-Ar dating to obtain absolute ages.

For age determination in sedimentary strata, it is best to find minerals from volcanic ash interbeds; otherwise, one must attempt to use detrital zircons. The ages of newly formed zircons from volcanic ash roughly approximate depositional ages, while the youngest ages from detrital zircons can constrain the maximum depositional age of a stratum. However, due to low-temperature lead loss, the measured age of a single zircon may be younger than the depositional age of the sediment (Nelson, 2001).

Additionally, some foreign terrestrial strata have established reference chronostratigraphic frameworks, such as the ages of Permian tetrapod assemblage zones in the Karoo Basin of South Africa obtained primarily through CA-TIMS (Rubidge et al., 2013), the ages of the Upper Triassic Chinle Formation that yields dinosaur fossils in the United States (Irmis et al., 2011; Ramezani et al., 2011), and the ages of the dinosaur-bearing Chañares Formation (Marsicano et al., 2016) and Ischigualasto Formation (Rogers et al., 1993; Martinez et al., 2011) in South America. Recent ages obtained from the Ecca Group in South Africa are significantly younger than those from the overlying Beaufort Group that contains Permian tetrapods (McKay et al., 2015), though paleomagnetic and paleontological data do not support this conclusion (Barbolini, 2014; Tohver et al., 2015; Belica et al., 2017). After years of work, China has preliminarily established a tetrapod sequence for terrestrial Permian and Triassic strata (Table 1) (primarily referencing Li and Cheng (1995) and Li et al. (2008)). If Chinese terrestrial strata can be correlated with foreign strata based on fossils such as tetrapod assemblages, chronological ages can also be obtained.

The following discussion addresses major Chinese terrestrial Permian and Triassic strata, divided by region: the Junggar and Turfan-Hami basins of Xinjiang, the North Qilian area, the North China area, and the South China area.

2.1 The Junggar Basin and Turfan-Hami Basin of Xinjiang

The traditional stratigraphic division of the Permian in the Junggar Basin includes, from bottom to top, the Lower Jijicao Group, Upper Jijicao Group, and Lower Cangfanggou Group. The Lower Jijicao Group consists primarily of bathyal-shelf deposits with well-developed volcanic rock series and is therefore not discussed in this paper. The Upper Jijicao Group includes, from bottom to top, the Wulabo, Jingjingzigou, Lucaogou, and Hongyanchi formations. The Lower Cangfanggou Group includes, from bottom to top, the Quanzijie, Wutonggou, and Guodikeng formations. In the Turfan Basin, the equivalent of the Upper Jijicao Group is the Taodong Group, comprising the Daheyan and Taerlang formations, which are also overlain by the Lower Cangfanggou Group. The Taerlang Formation is equivalent to the Lucaogou and Hongyanchi formations, and some researchers also use the latter two formation names in the Turfan Basin. The Triassic sequences in both areas include, from bottom to top, the Jiucaiyuan, Shaofanggou, Karamay, Huangshanjie, and Haojiagou formations. The stratigraphic sequences on both sides of the Tianshan Mountains are generally considered to be roughly contemporaneous.

The work of Yang et al. (2010) at the Taoshuyuan section in Turfan has dramatically changed previous understanding. They obtained ages older than 300 Ma from the lower part of the Daheyan Formation using $^{40}\text{Ar}/^{39}\text{Ar}$, high-resolution SHRIMP, and ID-TIMS methods (Figure 1 [Figure 1: see original paper]), which should correspond to the Gzhelian Stage of the Upper Carboniferous, though the upper part of this formation may reach the base of the Sakmarian Stage (Yang et al., 2010). The age of the Daheyan Formation was considered in the *Chinese Stratigraphic Dictionary* to be equivalent to the Chuanshanian Series to the lower part of the Yangxin Series.

The Lucaogou Formation was originally named at the 1976 Northwestern Stratigraphic Conference and was already used in *Mesozoic Vertebrate Fossil Strata of Northern Xinjiang* published in 1980; it was not, as stated in *Chinese Stratigraphic Dictionary: Permian*, “named by the Xinjiang Stratigraphic Table Compilation Group in 1981.” For the evolution of the name before its formal establishment, see Zhao Xijin (1980) Table 1. Based on the paleoniscoid fish fossils found, its age was considered “Late Permian” (Liu and Ma, 1973), but it was not excluded that it might include “Early Permian” (Zhao, 1980). Based on the age of 301 Ma at the top of the lower member of the Daheyan Formation and an ID-TIMS age of 281.39 Ma from volcanic ash in shale at the top of the Hongyanchi Formation (Figure 1), it is inferred to correspond to the middle-lower Sakmarian Stage to the base of the Artinskian Stage (Yang et al., 2010). Consequently, the age of *Urumqia* from this formation is consistent with that of most *Seymouriamorpha* abroad (Zhang et al., 1984), and it represents the old-

est known Permian tetrapod fossil in China. The Hongyanchi Formation was previously considered to be Late Yangxinian in age, but based on dating results it should be roughly equivalent to the Artinskian Stage (Yang et al., 2010).

The Quanzijie Formation was once considered Early Triassic deposition, but later, based on discovered plants, bivalves, and tetrapods, it was determined to be “Late Permian,” possibly equivalent to the Wuchiapingian Stage (Jin et al., 2000). Zhao Xijin (1980) had already proposed that the contact between the Quanzijie and Hongyanchi formations is unconformable, representing a relatively long depositional hiatus. However, this hiatus has often been ignored as a minor gap. Yang et al. consider the Quanzijie Formation to be roughly equivalent to the Capitanian Stage. Lucas (2001) grouped the dicynodonts found from the Quanzijie to Guodikeng formations into *Dicynodon*, thereby considering their age equivalent to the South African dicynodont zone. According to recent isotopic dating results, the dicynodont zone began at about 255.2 Ma (Rubidge et al., 2013). However, Lucas’s grouping has not been widely accepted (Kammerer et al., 2011), although he recently maintained his viewpoint (Lucas, 2017). *Doupilosaurus sunensis* was reported from the Quanzijie Formation (Sun, 1978), but its systematic position among dicynodonts requires further study and is currently insufficient to provide a basis for correlation. According to Yang et al. (2010), this depositional hiatus is about 15 Myr.

Based on ID-TIMS dating results from the top of the Wutonggou Formation (Figure 1), this formation is essentially Wuchiapingian in age (Yang et al., 2010).

The upper part of the Guodikeng Formation yields *Lystrosaurus*. *Lystrosaurus* has long been used as a marker for the beginning of the terrestrial Triassic, but later co-occurrence of *Lystrosaurus* and dicynodonts was discovered in China and South Africa (Cheng, 1993; Smith and Botha, 2005). The Permian-Triassic boundary in South Africa has long been marked by the disappearance of *Dicynodon*, that is, the disappearance of the Permian tetrapod fauna (Smith and Botha, 2005; Ward et al., 2005). However, recent discoveries of plant and animal fossils at the classic Old Lootsberg Pass locality in South Africa and an age of (253.48 ± 0.15) Ma from about 60 m below this boundary suggest that this boundary may be older than the marine boundary. The Permian-Triassic boundary in the Karoo Basin may be positioned higher or not preserved (Gastaldo et al., 2015). Some argue that the dicynodont fossils and volcanic ash layers at this section may be reworked and unreliable. Furthermore, recent work indicates that the Permian-Triassic boundary is not preserved in the distal side of the Karoo Basin, while the transitional layer is more completely preserved on the proximal side, and the disappearance of *Daptocephalus* marks the beginning of the Triassic (Rubidge et al., 2016; Viglietti et al., 2016). Based on studies of various plant and animal fossils, the Permian-Triassic biotic transition occurred within the Guodikeng Formation, and the Permian-Triassic boundary proposed in recent years also lies within this formation (Cao et al., 2008; Liu and Abdala, 2017). Currently, effective means for more precise correlation with marine strata are still lacking.

The Jiucaiyuan Formation, especially its middle and lower parts, yields abundant tetrapod fossils belonging to the *Lystrosaurus* Zone, and its age is generally considered early Early Triassic. The Shaofanggou Formation is fossil-poor and is currently assigned to the Early Triassic based on its similar spore-pollen assemblage to the Jiucaiyuan Formation. It has a disconformable contact with the underlying strata (Li et al., 1986). A reasonably well-preserved archosauriform fossil discovered in this formation in recent years may provide additional chronological information.

Different definitions of the top and bottom boundaries of the Karamay Formation have led to different views on its age. According to Zhao Xijin (1980), it has a disconformable contact with the underlying Shaofanggou Formation, whereas Li Peixian et al. consider it a conformable contact (Li et al., 1986). The formation is generally considered Middle Triassic in age, but Li Peixian et al. (Li et al., 1986), based on spore-pollen studies, suggested that the lower part of the Karamay Formation may be Ladinian, while the upper part may include the Upper Triassic. Shi Xiao et al. (Shi et al., 2014) recently reached a similar conclusion. Zhao Xijin (1980) assigned the fish-bearing horizon at the top of the Karamay Formation, adopted at the 1976 Northwestern Stratigraphic Conference, to the Huangshanjie Formation and considered it Late Triassic in age, mainly based on the discovery of the supposed aetosaur *Fukangolepis barbaros* (Young, 1978) and the long-dorsal-finned fish *Fukangichthys longidorsalis* (Su, 1978). However, *Fukangolepis* is actually partial skeleton of a kannemeyeriiform, so it cannot be used as evidence. Moreover, *Fukangichthys* is distantly related to the Late Triassic *Tanaocrossus* or *Scanolepis*, so the discovered vertebrates cannot indicate that the Karamay Formation includes the Late Triassic (Lucas and Hunt, 1993).

On the northwestern margin of the Junggar Basin, the upper member of the Karamay Formation is assigned to the Late Triassic, and the lower member to the late Middle Triassic-early Late Triassic (Luo et al., 2015). This is inconsistent with the depositional sequence on the southern margin (see Luo et al., 2015), and the ages may also be inconsistent, so it cannot be used to discuss the age of strata on the southern margin.

The Huangshanjie Formation is rich in fossils, including macroplants, spores and pollen, insects, and bivalves. In the Turfan-Hami Basin, based on spore-pollen studies, its age is Late Triassic (Yin, 1994) or early to middle Late Triassic (Liu, 2001). Based on macroplant fossils, the age is determined to be Carnian or Carnian to Norian (Sun G et al., 2010).

The Haojiagou Formation is rich in plant fossils. Based on macroplant fossils, its age is determined to be Late Triassic, possibly Norian to Rhaetian (Sun G et al., 2010). Based on spore-pollen assemblages, Lu Yuanzheng and Deng Shenghui (2005) divided it into two assemblages: the *Alisporites-Chordasporites-Chasmatosporites* Assemblage and the *Aratrisporites-Alisporites-Chasmatosporites* Assemblage, placing the Triassic-Jurassic boundary at the top of this formation (Lu and Deng, 2005). Huang Pin (2006) subdivided the

lower assemblage of Lu and Deng (2005) into two assemblages and proposed that only the very bottom belongs to the Upper Triassic, while the upper part belongs to the Lower Jurassic.

2.2 The North Qilian Area

The Permian and Triassic strata in this area include the Taiyuan, Shanxi, Dahuanggou, Yaogou, Qingtoushan, Sunan, Lugou, Dingjiayao, and Nanying' er groups (Jin et al., 2000; Yang et al., 2000; Liu et al., 2012). The Taiyuan and Shanxi formations here differ in age from their namesakes in the Taiyuan section. The Dahuanggou Formation should be late Cisuralian in age (Sun et al., 1992). The Yaogou Formation was originally considered "Late Permian," but the Dashankou Fauna discovered in the overlying Qingtoushan Formation is Guadalupian (Roadian or Wordian) in age (Rubidge, 2005; Liu et al., 2009; Lucas, 2017). Therefore, its age is temporarily assigned to the early-middle Guadalupian, making the Yaogou Formation likely late Cisuralian. The dicynodont fossil *Dicynodon sunanensis* from the top of the Sunan Formation (Li et al., 2000) was later revised as *Turfanodon bogdaensis* (Kammerer et al., 2011), with a late Lopingian age. The mixed Cathaysian-Angaran flora from the lower part of the Sunan Formation is Wuchiapingian in age (Sun K Q et al., 2010). Thus, part of the Capitanian deposits may be missing between the Qingtoushan and Sunan formations (Figure 1 [Figure 1: see original paper]).

2.3 The North China Area

The typical Permian and Triassic section in this area traditionally includes, from bottom to top, the Taiyuan, Shanxi, Lower Shihhotse, Upper Shihhotse, Sunjiagou, Liujiagou, Heshanggou, Ermaying, Tongchuan, Yongping, and Wayaopu formations.

Profiles analyzed for detrital zircons using LA-ICP-MS in this region include those from Xishan, Taiyuan (Liu C et al., 2014; Sun et al., 2014), Pingquan, Hebei (Ma et al., 2011; Wei et al., 2015), and Xiabancheng, Chengde, Hebei (Meng et al., 2014). A volcanic tuff interlayer in the upper part of the "Ermaying Formation" near Shihucun, Chengde County, yielded a LA-ICP-MS zircon U-Pb weighted mean age of (234.2 ± 2.6) Ma (Zhang Y Q et al., 2016). Additionally, multiple volcanic tuff interlayers in the Ermaying and Tongchuan formations along the Yellow River have been dated using LA-ICP-MS, SHRIMP, and CA-TIMS (Liu et al., 2013; 2018; Wang et al., 2014; Zhang et al., 2014; 2017). Due to the large errors of the method, LA-ICP-MS dating results are not discussed below.

The Taiyuan Formation is primarily marine-terrestrial transitional facies, traditionally considered Late Carboniferous to Early Permian in age, though the exact position of the Carboniferous-Permian boundary remains controversial. Because the base of the Permian System is defined by the first appearance of the conodont *Streptognathodus isolatus*, Wang Chengyuan and Kang Peiquan

(Wang and Kang, 2000) considered the Taiyuan Formation to be Permian in age, with the base of the Miaogou Limestone being very close to the Permian base. However, the Taiyuan Formation here is used in a narrow sense, not including the Jinci Sandstone, equivalent to the usage in Wang and Qi (2003). The *Sweetognathus whitei* zone has been discovered at the top of the Taiyuan Formation in Henan, Shandong, and other places, with an age of the Lengwu Stage (Wang and Qi, 2003) or Artinskian Stage (Mei and Henderson, 2001).

The Shanxi Formation represents coastal and inland swamp deposits, generally lacking limestone interbeds, though the Shanxi Formation in Xishan, Taiyuan is mainly marine. It corresponds to the Chuanshanian Series to the lower part of the Yangxin Series (equivalent to the upper Cisuralian Series) (Jin et al., 2000). Based on the contained *Caulopteris wudaensis-Paratingia datongensis* assemblage, its age in the northern Helan Mountains is late Early Permian, equivalent to the Sakmarian and Artinskian stages (Sun and Deng, 2003). Based on spore-pollen assemblages, the Shanxi Formation in Baode, Shanxi corresponds to part of the Artinskian Stage (Liu et al., 2015). Here, the Shanxi Formation is roughly correlated with the upper Artinskian Stage.

The Lower Shihhotse Formation consists mainly of fluvial and alluvial plain deposits. Based on plant fossils, it is considered equivalent to the middle Yangxin Series (roughly equivalent to the upper Cisuralian to middle-lower Guadalupian Series) (Jin et al., 2000). Based on spore-pollen assemblages, its age is roughly equivalent to part of the Kungurian to Wordian stages (Liu et al., 2015).

The Upper Shihhotse Formation is late Guadalupian to early Lopingian in age. The tetrapod assemblage discovered near the top of this formation in Jiyuan, Henan is roughly equivalent in age to the *Cistecephalus* Assemblage Zone of South Africa, so its upper boundary is about 255 Ma (Rubidge et al., 2013; Liu J et al., 2014), extending to approximately the end of the Wuchiapingian Stage. The author recently discovered volcanic tuff layers in the upper part of this formation, and dating them can test this conclusion. The Yujiabeigou Formation in the northern marginal area of Inner Mongolia is marine-terrestrial transitional facies, containing foraminifera, bryozoans, bivalves, brachiopods, and other marine fossils, as well as multiple volcanic tuff layers. Its age is determined as Guadalupian based on marine fossils (Sun et al., 2016). Its flora is the *Gigantonoclea hallei-Fasciopsis spp.-Lobatanularia heianensis* plant assemblage, which also supports the geological age of the Upper Shihhotse Formation.

The Sunjiagou Formation is mainly terrestrial but has marine interbeds in Henan and other places, and grades into marine deposits in the Weibei area of Shaanxi. Its age is generally considered late Lopingian (Liu et al., 2011, 2015), but some consider it Early Triassic (Yin and Lin, 1979). Multiple layers of pareiasaur fossils have been found in the Sunjiagou Formation in Shanxi, with pareiasaur horizons near the top of the formation at Liulin Beigou (Gao, 1983). Pareiasaurs are globally recognized as a Permian group, with their last appearance in South Africa occurring 24 m below the boundary and not extending into the Triassic (Benton, 2016; Viglietti et al., 2016). Therefore, current vertebrate evidence

does not support placing the Permian-Triassic boundary significantly below the boundary between the Sunjiagou and Liujiagou formations.

The Liujiagou Formation is dominated by sandstone with sparse fossils. *Pleuromeia jiaochengensis* was discovered in the Qinshui Basin, Shanxi (Wang and Wang, 1982), indicating an Early Triassic age. In addition, fragmentary tetrapod fossils have been found in this formation (personal communication from Li Jinling), indicating that tetrapods could survive even under the high-temperature conditions of that time (Sun et al., 2012).

The Heshanggou Formation is generally considered late Early Triassic in age, mainly based on the discovery of *Pleuromeia* fossils (Wang et al., 1978). The northern Shaanxi kannemeyeriiform fauna occurs at the top of this formation and the bottom of the Ermaying Formation and can be correlated with the *Cynognathus* B Subzone, considered late Early Triassic in age, placing the Early-Middle Triassic boundary within the Ermaying Formation (Sun, 1980). Lucas (1998, 2010) has consistently held this view, while Ochev and Shishkin (1989), Shishkin et al. (1995), and Rubidge (2005) 倾向于认为犬颌兽 B 亚带是安尼期。Ottone et al. (2014) 在阿根廷的 Quebrada de los Fósiles 组顶部用 SHRIMP 得出 (235.8 ± 2.0) Ma 的年龄, 并认为犬颌兽 B 亚带年龄更新, 应该是卡尼期。这与二马营组二段下部 243.5 Ma 的测年结果不符, 这里不采用。二马营组的测年结果支持早中三叠世分界位于和尚沟组内部的假说 (Liu et al., 2018)。

The Ermaying Formation is distributed in the Ordos and western Shanxi-eastern Henan stratigraphic subareas and is generally considered early Middle Triassic (Anisian) in age (Yang et al., 2000). Based on correlation between the Chinese kannemeyeriiform fauna and the *Cynognathus* C Subzone, its age should be late Anisian (Rubidge, 2005). Recent CA-TIMS dating obtained an age of 243.53 Ma from the lower part of the second member, supporting this conclusion (Figure 1) (Liu et al., 2018). A set of fluvial red sandstone-mudstone in the Xiabancheng-Pingquan area of Hebei was once considered part of the Ermaying Formation (Lu and Dou, 1982). Recent LA-ICP-MS dating results suggest this set of strata is Late Triassic in age (Meng et al., 2014; Wei et al., 2015; Zhang Y Q et al., 2016), which differs too much from the type locality. Therefore, some have suggested reinstating the name Huzhangzi Formation (Wei et al., 2015). Due to the limitations of the method itself, this age needs to be tested with better dating methods. However, the age of this set of strata has little relevance to the Ermaying Formation in the Ordos Basin.

The Tongchuan Formation originated from the first and second members of the former Yanchang Group, named by the Institute of Geology, Chinese Academy of Geological Sciences in 1965, with the type section at Jinsuoguan, Qishuihe, Tongchuan, Shaanxi. Its age is generally considered late Middle Triassic (Ladinian). There is a tuff marker bed in the second member, second band of the Tongchuan Formation. SHRIMP dating suggests a Ladinian age (Liu et al., 2013), and recent CA-TIMS has yielded a more precise age of 241.48 Ma (Figure 1) (Liu et al., 2018). The oil shale at the very top contains numerous tuff layers, with SHRIMP results of (241.3 ± 2.4) Ma and (239.7 ± 1.7) Ma. Wang

Duoyun et al. proposed that the Yanchang Formation in the narrow sense includes the Middle Triassic (Wang et al., 2014). Correspondingly, the Yongping Formation (originally referring to the fourth member of the Yanchang Group, but here adopting the usage in *National Stratigraphic Multi-division Correlation Study: Rock Stratigraphy of Shaanxi Province* (1998), which includes the former Hujiacun Formation and corresponds to the third and fourth members of the Yanchang Group) should include the Ladinian and Carnian stages. The Wayaopu Formation is equivalent to the former fifth member of the Yanchang Group. Through plant assemblage correlation, this set of strata lacks the latest Triassic and is probably around the Norian Stage.

2.4 The South China Area

Permian and Triassic strata in South China are mainly marine, but during the Permian-Triassic transition, terrestrial and marine-terrestrial transitional deposits occurred along the margin of the Kangdian Oldland, and during the Middle Triassic there were marine-terrestrial transitional and terrestrial strata (e.g., Badong Formation), which transitioned to terrestrial coal-bearing strata (e.g., Xujiache Formation) in the Late Triassic.

The Permian-Triassic transition terrestrial strata (including marine-terrestrial transitional facies) in western Guizhou and eastern Yunnan include, from bottom to top, the Xuanwei, Kayitou, and Dongchuan formations. Based on the Gigantopteris flora produced, the Xuanwei Formation is Lopingian (Late Permian) in age; it conformably or disconformably overlies the Emeishan Basalt, whose eruption age has recently been determined at about 260 Ma (Li et al., 2014), indicating that its base essentially coincides with the base of the Lopingian Series. Based on previous SHRIMP zircon dating from layer 68 of the Chahe section, it was thought that the top of the Xuanwei Formation was coeval with layer 28 of the Meishan section (Yu et al., 2008). Later ID-TIMS dating yielded an age of (252.30 ± 0.07) Ma, consistent with the age of layer 25 of the Meishan section (Shen et al., 2011).

The Kayitou Formation occupies a marine-terrestrial transitional position, containing marine, marine-terrestrial transitional, and purely terrestrial facies. It is also a transitional unit between the Permian and Triassic, and its exact age is quite controversial: e.g., earliest Early Triassic (Chen et al., 2011; Liu and Yao, 2002), or ranging from Lopingian to Early Triassic (Wang, 2001; 2002). Due to the diachronous nature of lithostratigraphy, the specific age of the Kayitou Formation may not be the same across different sections and requires case-by-case analysis: the Chahe and Guanchachong sections are latest Changhsingian, while the Lubei section ranges from Changhsingian to Induan (Zhang H et al., 2016). Correspondingly, the Dongchuan Formation is basically Induan in age, but in some places may extend to the latest Permian. However, some researchers, based on studies of these and some new sections, have proposed that the Kayitou Formation everywhere ranges from Lopingian to Early Triassic (Chu et al., 2016, 2017).

Member II of the Badong Formation is dominated by terrestrial facies and yields the terrestrial tetrapods *Lotosaurus* and *Yuanansuchus* (Zhang, 1975; Liu and Wang, 2005; Liu, 2016). The age of the Badong Formation has long been controversial. It was once entirely assigned to the Anisian or Ladinian, later considered Middle Triassic (Anisian to Ladinian), and in the *Chinese Stratigraphic Dictionary: Triassic* it was considered Anisian. Although ammonites and other marine fossils have been found, they are difficult to correlate with fossils from the stage-type areas, which is the reason for the controversy. The Anisian age is basically consistent with paleomagnetic study results (Huang and Opdyke, 2000). Our recent analysis of detrital zircons concluded that it is younger than the Ladinian (Hagen et al., 2018). However, due to the LA-ICP-MS method limitations, this age is not highly reliable.

The Xujiahe Formation in the Sichuan Basin has abundant plant fossils and has yielded the oldest dinosaur footprints in China. The underlying Xiaotangzi Formation is determined to be Norian based on marine bivalves, so the Xujiahe Formation is roughly dated as Rhaetian. However, the Shazhenxi Formation in Hubei, and the Pujiacun, Ganhaizi, and Shezi formations in central Yunnan, which have the same plant assemblage, are considered Norian to Rhaetian in age (Yang et al., 2000), while the Yingzuishan Formation in Sangzhi, Hunan is considered middle-late Norian. Detrital zircons roughly date it as Late Triassic. Additionally, primarily through magnetostratigraphy and astronomical cyclostratigraphy studies, correlation with strata from Italy and the Newark Basin in the United States has led to the conclusion that its age is latest Triassic Rhaetian (Li et al., 2017).

In the past two decades, with improvements in dating methods, some progress has been made, and a general chronological framework for Chinese Permian-Triassic strata has been established. However, understanding of the ages of many strata still does not reach the stage level. Finer chronostratigraphic boundary studies are even more difficult. The most closely watched terrestrial Permian-Triassic boundary in North China and Xinjiang has not yet made substantive progress and requires more high-precision dating to resolve the ages of terrestrial strata.

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