第56卷 第1期
2018年1月

古 脊 椎 动 物 学 报
VERTEBRATA PALASIATICA

pp. 16–24
figs. 1–3

DOI: 10.19615/j.cnki.1000-3118.170808

High-precision temporal calibration of Middle Triassic vertebrate biostratigraphy: U-Pb zircon constraints for the *Sinokannemeyeria* Fauna and *Yonghesuchus*

LIU Jun[1,2] Jahandar RAMEZANI[3] LI Lu[1] SHANG Qing-Hua[1]
XU Guang-Hui[1] WANG Yan-Yin[1] YANG Jia-Sheng[1,2]

(1 *Key Laboratory of Vertebrate Evolution and Human Origins of Chinese Academy of Sciences*, *Institute of Vertebrate Paleontology and Paleoanthropology*, *Chinese Academy of Sciences* Beijing 100044, China liujun@ivpp.ac.cn)
(2 *University of Chinese Academy of Sciences* Beijing 100049, China)
(3 *Department of Earth*, *Atmospheric and Planetary Sciences*, *Massachusetts Institute of Technology* Cambridge, Massachusetts 02139, USA)

Abstract Tetrapod assemblages provide a useful means for global correlation of the terrestrial Triassic sedimentary deposits, but currently no reliable temporal framework has been achieved for the Middle Triassic tetrapod assemblages. Here we report U-Pb zircon chemical abrasion–thermal ionization mass spectrometry dates for five volcanic ashes interbedded with vertebrate fossils from the Ermaying and Tongchuan formations of China. Our results support a late Anisian age for the *Sinokannemeyeria* Fauna and an early Ladinian age for *Yonghesuchus* Fauna. It is now possible, through biostratigraphic correlation, to provide accurate ages to other Middle Triassic successions such as the Upper *Cynognathus* Assemblage Zone of the Karoo of South Africa, the *Eryosuchus* fauna of the Donguz Suite of Russia and the Karamayi Formation of Xinjiang, China. The base of Anisian (Lower/Middle Triassic boundary) should lie below the base of the Ermaying Formation in the Ordos Basin.

Key words Middle Triassic, Ermaying Formation,Tongchuan Formation, *Sinokannemeyeria* Fauna, *Yonghesuchus*, U-Pb dating

Citation Liu J, Ramezani J, Li L et al., 2018. High-precision temporal calibration of Middle Triassic vertebrate biostratigraphy: U-Pb zircon constraints for the *Sinokannemeyeria* Fauna and *Yonghesuchus*. Vertebrata PalAsiatica, 56(1): 16–24

1 Introduction

The Triassic is a very important period in vertebrate history as it marks the first appearance of mammals (Lucas and Luo, 1993; Luo, 2007; Martinez et al., 2011), dinosaurs (Nesbitt et al., 2010; Martinez et al., 2011; Ramezani et al., 2011; Sues, 2016), and turtles (Li et al., 2008; Schoch and Sues, 2015). Because of the rich and diverse vertebrate record from the Triassic, tetrapod fossils have been used for global biostratigraphic correlation of Triassic

国家重点基础研究发展计划项目(编号：2012CB821902)、国家自然科学基金(批准号：41472017, 41661134047)、现代古生物学和地层学国家重点实验室基金(编号：20161101)、中国科学院战略性科技先导专项(B类) (编号：XDPB05)和古生物化石发掘修理专项经费资助。
收稿日期：2017-06-23

continental sedimentary successions (e.g., Lucas, 2010). However the correlation of Triassic vertebrate biozones to marine biozones have been controversial, and progress hindered by the lack of reliable radioisotopic age constraints.

The situation has improved in the relatively recent past and radioisotopic dates are now available for some Triassic deposits (e.g., Mundil et al., 2010). To date the only Traissic tetrapod-bearing terrestrial deposits for which radiometric dates are available are the Ischigualasto tetrapod assemblage (Rogers et al., 1993; Martinez et al., 2011), the Chañares Formation (Marsicano et al., 2016), the Chinle Formation (Riggs et al., 2003; Irmis et al., 2011; Ramezani et al., 2011), the Ermaying and Tongchuan Formations (Liu et al., 2013), and the Puesto Viejo Formation (Ottone et al., 2014). However, the zircon U-Pb sensitive high-resolution ion microprobe (SHRIMP) dates reported by Liu et al. (2013) for volcanic ash beds from the Ermaying and Tongchuan formations of the Ordos Basin, China have large error bars. We now report new high resolution chemical abrasion–thermal ionization mass spectrometry (CA-TIMS) dates for the same ash beds.

Apart from the *Cynognathus* Assemblage Zone of the Karoo Supergroup of South Africa, the Ermaying Formation of the Ordos Basin of China preserves one of the most prolific Middle Triassic terrestrial tetrapod assemblages. The Lower Ermaying Formation has been biostratigraphically correlated with the *Cynognathus* Subzone B Assemblage, and the Upper Ermaying Formation (*Sinokannemeyeria* Fauna) correlated with *Cynognathus* Subzone C assemblage (Lucas, 2010; Rubidge, 2005). *Yonghesuchus* from the Tongchuan Formation is closely related to *Gracilisuchus* from the Chañares Formation of Argentina (Butler et al., 2014).

2 Geological setting

The Ordos Basin is an intracontinental basin situated in western north China with an 8000 m thick sedimentary infill of Paleozoic to Cenozoic age. The Triassic succession comprises the Liujiagou, Heshangou, Ermaying, Tongchuan and Yanchang formations. The Ermaying and Tongchuan Formations in turn each comprise two members. Member II of the Tongchuan Formation comprises two beds of which Bed II has a colorful basal tuff layer which serves as a regional marker layer (Fig. 1).

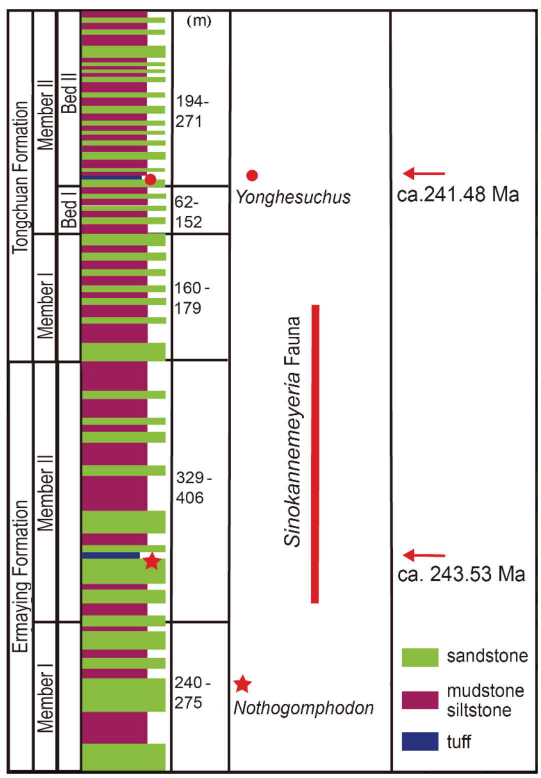

Fig. 1 The stratigraphic column of the Ermaying and Tongchuan formations of Ordos Basin (China) along with tetrapod fossils and U-Pb geochronologic results of this study

3 Methods and results

Volcanic ash samples and vertebrate fossils were collected from different stratigraphic horizons in the Ermaying and Tongchuan Formations from five localities in Shanxi Province, China (Table 1). Extensive field prospecting for tetrapod fossils was undertaken at each locality to establish the correlative vertebrate biozone. Stratigraphic sections were measured at all localities to establish the stratigraphic position of each ash relative to lithostratigraphic markers and/or fossils.

Table 1 The localities and horizons of five samples

Sample	Locality	GPS co-ordinate		Formation
LT	Jiaokou	N 36°39′54″	E 110°36′24″	Tongchuan
ST	Sangbi	N 36°37′29″	E 110°38′7″	Tongchuan
JD	Shixi	N 37°26′16″	E 110°39′23″	Ermaying
SJ	Sanjiao	N 37°17′12″	E 110°42′23″	Ermaying
ME	Mengjiata	N 37°17′12″	E 110°42′23″	Ermaying

Samples JD, ME and SJ are all from Member II of the Ermaying Formation but their relative positions on the stratigraphic columns are difficult to determine. Sample SJ was previously mistakenly assigned to the Tongchuan Formation (Liu et al., 2013), and of all the above samples, SJ is the only one which has good biostratigraphic provenance.

Two tuff samples were processed from the Tongchuan Formation: sample LT is from the tuff marker bed at Jiaokou, and sample ST is from Sangbi and was collected 15 m above the stratigraphic horizon of the holotype of *Yonghesuchus* (Liu et al., 2001) (Fig. 2).

We present new CA-TIMS U-Pb single-zircon data for five samples from possible two key volcanic ash layers from the Ermaying and Tongchuan formations, constraining 2 million years of Triassic terrestrial history. Fig. 3 shows the relative stratigraphic positions of the dated ash beds.

Ermaying Formation Sample JD Six prismatic zircons were analyzed, five of which yield a weighted mean $^{206}Pb/^{238}U$ date of (243.29 ± 0.14/0.17/0.31) Ma and a mean square of weighted deviates (MSWD) of 1.1. The sixth analysis yielded much older dates that is attributed to inheritance and is excluded (see Table 2 for an explanation of error notations).

Sample SJ Five prismatic zircons were analyzed, four of which yield a weighted mean $^{206}Pb/^{238}U$ date of (243.528 ± 0.069/0.13/0.29) Ma (MSWD=0.32) (Fig. 4). The fifth analysis yielded much older dates that is attributed to inheritance and is excluded (see Table 2 for an explanation of error notations).

Sample ME Five analyses with dates as old as 1.744 Ga suggest significant detrital input due to sedimentary reworking. However, the youngest analysis with $^{206}Pb/^{238}U$ dates of (243.53 ± 0.21) Ma provide a maximum estimate for the age of deposition of the bed, consistent with its stratigraphic position.

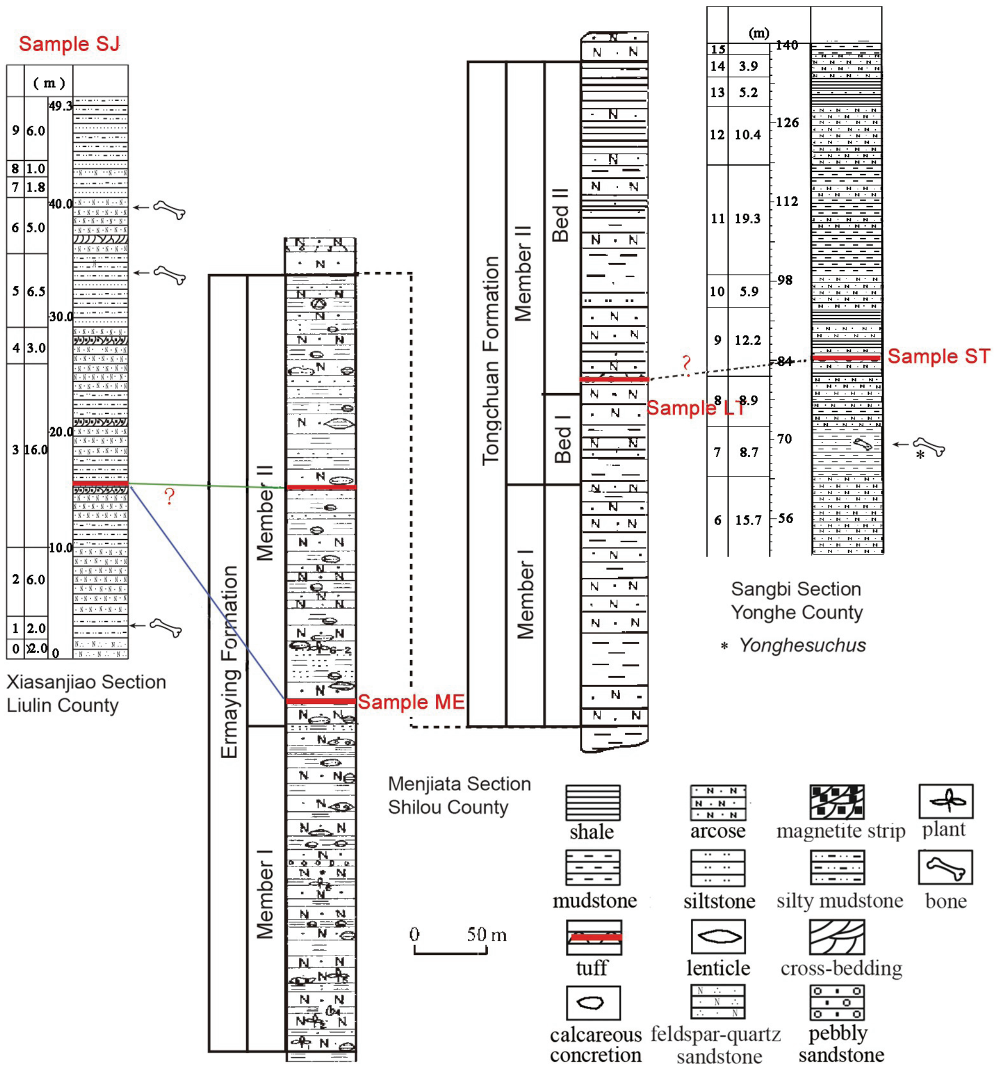

Fig.2 The correlation of three stratigraphic columns to show the relative position of samples
LT was collected from Jiaokou, but its position is showed on the Menjiata section. JD is not showed here beacause it is hard to determine its exact position on the stratigraphic column.The Menjiata section is from Regional Geological Report of Shilou, the Sangbi section is from Liu et al. (2001)

Tongchuan Formation Sample LT This sample contains abundant, clear, short, prismatic zircons from which six individual grains were analyzed. These define a tight cluster with a weighted mean $^{206}Pb/^{238}U$ date of (241.369 ± 0.061/0.12/0.29) Ma (MSWD = 0.83) (Fig. 3) (see Table 2 for an explanation of error notations).

Sample ST This sample contains abundant, clear, short, prismatic zircons from which five individual grains were analyzed. These define a tight cluster with a weighted mean $^{206}Pb/^{238}U$ date of (241.482 ± 0.074/0.13/0.29) Ma (MSWD=0.60) (Fig. 4) (see Table 2 for an explanation of error notations).

4 Discussion and conclusion

Our geochronologic results establish CA-TIMS dates for Member II of the Ermaying Formation and Member II (lower Bed II) of the Tongchuan Formation. In particular, because of targeted fossil collecting at each ash locality, the vertebrate assemblage zone provenance of the ashes has also been established and dated: 243.53 Ma (late Anisian) for the lower part of *Sinokannmeyeria* Fauna, and 241.48 Ma (early Ladinian) for *Yonghesuchus*.

Global correlation of Mid-Triassic tetrapod bearing faunas Based on the co-occurrence of *Shansiodon* from both the *Sinokannmeyeria* Fauna of the Ermaying Formation and the Subzone C of the *Cynognathus* Assemblage Zone of the Beaufort Group of South Africa (Hancox et al., 2013), the *Sinokannmeyeria* Fauna has been correlated to the South

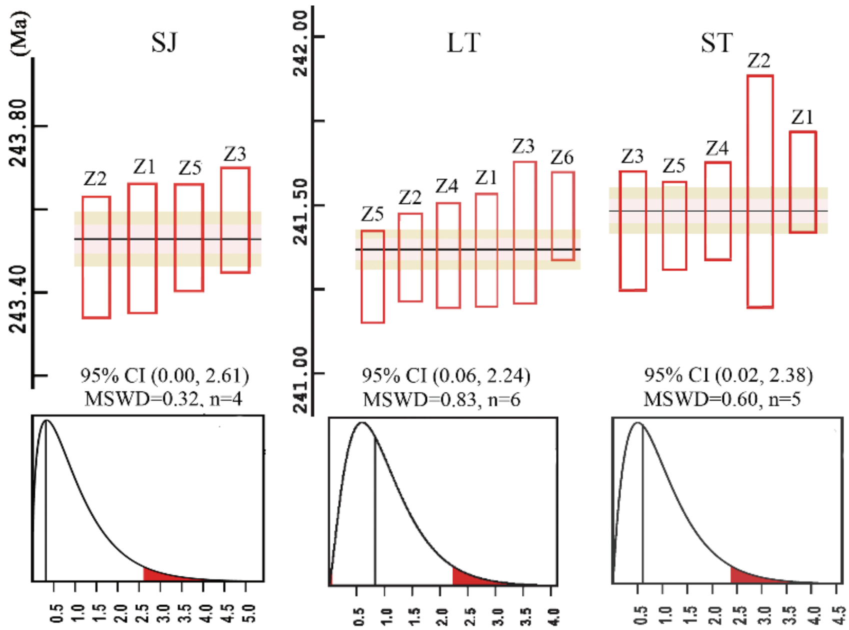

Fig. 3 Age distribution plots for analyzed zircon samples SJ, LT and ST
Bar heights represent 2σ analytical uncertainty of individual zircon analyses
MSWD. mean square of weighted deviates

Table 2 Summary of calculated U-Pb ages and their uncertainties

Sample	$^{206}Pb/^{238}U$ age (Ma)	Error (2σ) X	Error (2σ) Y	Error (2σ) Z	N	MXWD
LT	241.369	0.061	0.12	0.29	6	0.83
ST	241.482	0.074	0.13	0.29	5	0.60
JD	243.29	0.14	0.17	0.31	5	1.1
SJ	243.528	0.069	0.13	0.29	4	0.32
ME	≤243.53	–	–	–	–	–

Note: All dates are based on single-zircon CA-TIMS analyses. Uncertainties reported at 2σ level. X. internal (analytical) uncertainty in the absence of all external or systematic errors; Y. incorporates the U-Pb tracer calibration error; Z. includes X and Y, as well as the uranium decay constant errors of Jaffey et al. (1971); N. number of analyses included in the weighted mean date.

African *Cynognathus* C subzone of the Beaufort Group. Our research demonstrates a CA-TIMS date of 243.53 Ma (late Anisian) for the *Sinokannemeyeria* Fauna which is in agreement with the proposal of Rubidge (2005) who, based on biostratigraphy, considered the *Cynognathus* C subzone to be late Anisian, and correlated it with other Pangaean successions. Utilizing the co-occurrence of the cynodont *Nothogomphodon* (Liu and Abdala, 2015), the *Sinokannmeyeria* Fauna can be correlated to Russian *Eryosuchus* Fauna which has long been considered to be Middle Triassic (late Anisian to Ladinian) (Shishkin et al., 2000) and was correlated to the South African subzones B and C of the *Cynognathus* Assemblage Zone (Hancox, 1998; Rubidge, 2005). Our work supports the idea that *Eryosuchus* fauna is at least partially correlated to *Cynognathus* C subzone and is thus late Anisian.

The Puesto Viejo Formation (Group) of Argentina was also correlated with subzone C and assigned an age of late Anisian based on shansiodont *Vinceria* (Rubidge, 2005). However, a Carnian age (235.8 ± 2.0 Ma) is obtained by the SHRIMP U-Pb dating (Ottone et al., 2014). This dating is not concordant with the bearing tetrapods, and needs to be further tested.

Yonghesuchus is closely related to *Turfanosuchus* from the Karamayi Formation of Xinjiang, China and *Gracilisuchus* from the Chañares Formation of La Rioja Province, Argentina (Butler et al., 2014). Our research demonstrates a CA-TIMS date of 241.48 Ma (early Ladinian) for the *Yonghesuchus* Fauna which is earlier than the early Carnian age of the Chañares Formation (Marsicano et al., 2016), and indicates that the age of Karamayi Formation could extend to Ladinian or even Carnian.

These newly determined CA-TIMS dates in the Ordos Basin of China provide the first empirical evidence for Anisian and Ladinian ages respectively for the *Sinokannemeyeria* and *Yonghesuchus* faunas. This is of international significance as it is now possible to provide proof of age to other Middle Triassic successions which share biozone defining vertebrate taxa. In particular for the Anisian this is pertinent to the Upper *Cynognathus* Assemblage Zone of the Karoo of South Africa and the *Eryosuchus* fauna of the Donguz Suite of Russia, and for the Ladinian it applies to Chañares Formation of Argentina.

Age of the Ermaying Formation and the Lower/Middle Triassic boundary Recently, Late Triassic ages were reported for the Ermaying Formation of the Yanshan belt (Meng et al., 2014; Wei et al., 2015; Zhang et al., 2016). However, typical Ermaying Formation generally distributes in Ordos and West Shanxi-Henan stratigraphic regions, not in Yanshan belt (Yang et al., 2000); and the former name Huzhangzi Formation was reused to replace the name Ermaying Formation in Yanshan belt (Wei et al., 2015).

If we accept the similar deposit velocity for all the Ermaying Formation, the base of the Ermaying Formation here is assumed as ca. 245 Ma, much younger than the age of the base of Anisian (~247 Ma) and the base of Anisian (Lower/Middle Triassic boundary) should lie within the Heshanggou Formation, lower than current schemes (Li and Cheng, 1995; Yang et al., 2000).

Acknowledgements We thank Liu Yu-Feng, Xu Xu, Liu Yu-Dong for their work for collecting fossils and tuff samples. Corwin Sullivan and Sterling Nesbitt read and commented on an early version of this paper. Bruce Rubidge and Spencer Lucas reviewed the paper, and significantly improve it. The research was supported by the National Natural Science Foundation of China (41472017 and 41661134047), State Key Laboratory of Palaeobiology and Stratigraphy (Nanjing Institute of Geology and Palaeontology, CAS) (20161101), Chinese Academy of Sciences (XDPB05). Fossil collection was also supported by the excavation grant from the Chinese Academy of Sciences.

中三叠世脊椎动物生物地层的高精度时间校准：铀-铅锆石法测定的中国肯氏兽动物群和永和鳄年代

刘 俊[1,2] Jahandar RAMEZANI[3] 李 录[1] 尚庆华[1]
徐光辉[1] 汪衍胤[1] 杨嘉声[1,2]

(1 中国科学院古脊椎动物与古人类研究所，中国科学院脊椎动物演化与人类起源重点实验室 北京 100044)

(2 中国科学院大学 北京 100049)

(3 美国麻省理工学院地球、大气和行星科学系 坎布里奇 02139)

摘要：四足动物组合带是全球陆相三叠系对比的有力手段，但是迄今为止中三叠世的四足动物组合尚没有可靠的时间框架。报道了5个采自二马营组和铜川组，与四足动物化石共同产出的火山凝灰岩样品的锆石化学剥蚀-热电离质谱法年龄。结果表明中国肯氏兽动物群时代为安尼期晚期，而永和鳄的时代为拉丁期早期。通过生物地层对比，这一结果还为其他中三叠世的四足动物组合，如南非的犬颌兽带上部、俄罗斯的引鳄动物群以及新疆的克拉玛依组提供了准确的年龄。鄂尔多斯盆地下中三叠统界线应低于二马营组底界。

关键词：中三叠世，二马营组，铜川组，中国肯氏兽动物群，永和鳄，铀-铅锆石法测年

中图法分类号：P534.51 **文献标识码**：A **文章编号**：1000-3118(2018)01-0016-09

References

Butler R, Sullivan C, Ezcurra M et al., 2014. New clade of enigmatic early archosaurs yields insights into early pseudosuchian phylogeny and the biogeography of the archosaur radiation. BMC Evol Biol, 14(1): 128

Hancox P J, 1998. A stratigraphic, sedimentological and palaeonvironmental synthesis of the Beaufort-Molteno contact in the Karoo Basin. Ph. D thesis. Johannesburg: University of the Witwatersrand. 1–391

Hancox P J, Angielczyk K D, Rubidge B S, 2013. *Angonisaurus* and *Shansiodon*, dicynodonts (Therapsida, Anomodontia) from subzone C of the *Cynognathus* Assemblage Zone (Middle Triassic) of South Africa. J Vert Paleont, 33(3): 655–676

Irmis R B, Mundil R, Martz J W et al., 2011. High-resolution U-Pb ages from the Upper Triassic Chinle Formation (New Mexico, USA) support a diachronous rise of dinosaurs. Earth Planet Sci Lett, 309: 258–267

Li C, Wu X C, Rieppel O et al., 2008. An ancestral turtle from the Late Triassic of southwestern China. Nature, 456: 497–501

Li J L, Cheng Z W, 1995. A new Late Permian vertebrate fauna from Dashankou, Gansu, with comments on Permian and Triassic vertebrate assemblage zones of China. In: Sun A L, Wang Y Q eds. Sixth Symposium on Mesozoic Terrestrial Ecosystems and Biota, Short Papers. Beijing: China Ocean Press. 33–37

Li J L, Wu X C, Zhang F C, 2008. The Chinese Fossil Reptiles and Their Kin. 2nd ed. Beijing: Science Press. 1–473

Liu J, Abdala F, 2015. New discoveries from the *Sinokannemeyeria*-*Shansisuchus* Assemblage Zone: 2. A new species of *Nothogomphodon* (Therapsida: Therocephalia) from the Ermaying Formation (Anisian, Middle Triassic) of Shanxi, China. Vert PalAsiat, 53: 123–132

Liu J, Wu X C, Li J L, 2001. The first reptile from the Tongchuan Formation and its stratigraphical significance. Vert PalAsiat, 39: 67–71

Liu J, Li L, Li X W, 2013. SHRIMP U-Pb zircon dating of the Triassic Ermaying and Tongchuang formations in Shanxi, China and its stratigraphic implications. Vert PalAsiat, 51: 162–168

Lucas S G, 2010. The Triassic timescale based on nonmarine tetrapod biostratigraphy and biochronology. Geol Soc London Spec Publ, 334: 447–500

Lucas S G, Luo Z X, 1993. *Adelobasileus* from the Upper Triassic of West Texas: the oldest mammal. J Vert Paleont, 13(3): 309–334

Luo Z X, 2007. Transformation and diversification in early mammal evolution. Nature, 450: 1011–1019

Marsicano C A, Irmis R B, Mancuso A C et al., 2016. The precise temporal calibration of dinosaur origins. Proc Natl Acad Sci USA, 113(3): 509–513

Martinez R N, Sereno P C, Alcober O A et al., 2011. A basal dinosaur from the dawn of the dinosaur era in southwestern Pangaea. Science, 331: 206–210

Meng Q R, Wei H H, Wu G L et al., 2014. Early Mesozoic tectonic settings of the northern North China craton. Tectonophysics, 611(1): 155–166

Mundil R, Pálfy J, Renne P R et al., 2010. The Triassic timescale: new constraints and a review of geochronological data. Geol Soc London Spec Publ, 334: 41–60

Nesbitt S J, Sidor C A, Irmis R B et al., 2010. Ecologically distinct dinosaurian sister group shows early diversification of Ornithodira. Nature, 464: 95–98

Ottone E G, Monti M, Marsicano C A et al., 2014. A new Late Triassic age for the Puesto Viejo Group (San Rafael depocenter, Argentina): SHRIMP U-Pb zircon dating and biostratigraphic correlations across southern Gondwana. J South Am Earth Sci, 56: 186–199

Ramezani J, Hoke G D, Fastovsky D E et al., 2011. High-precision U-Pb zircon geochronology of the Late Triassic Chinle Formation, Petrified Forest National Park (Arizona, USA): temporal constraints on the early evolution of dinosaurs. Geol Soc Am Bull, 123: 2142–2159

Riggs N R, Ash S R, Barth A P et al., 2003. Isotopic age of the Black Forest Bed Petrified Forest Member, Chinle Formation, Arizona: an example of dating a continental sandstone. Geol Soc Am Bull, 115(11): 1315–1323

Rogers R R, Swisher C C, Sereno P C et al., 1993. The Ischigualasto tetrapod assemblage (Late Triassic, Argentina) and $^{40}Ar/^{39}Ar$ dating of dinosaur origins. Science, 260: 794–797

Rubidge B S, 2005. Re-uniting lost continents: fossil reptiles from the ancient Karoo and their wanderlust. S Afr J Geol, 108(3): 135–172

Schoch R R, Sues H D, 2015. A Middle Triassic stem-turtle and the evolution of the turtle body plan. Nature, 523: 584–587

Shishkin M A, Ochev V G, Lozovsky V R et al., 2000. Tetrapod biostratigraphy of the Triassic of Eastern Europe. In: Benton M J, Shishkin M A, Unwin D M et al. eds. The Age of Dinosaurs in Russia and Mongolia. Cambridge: Cambridge University Press. 120–139

Sues H D, 2016. Dating the origin of dinosaurs. Proc Natl Acad Sci USA, 113(3): 480–481

Wei H H, Wu G L, Duan L, 2015. Revisiting Triassic stratigraphy of the Yanshan belt. Sci China Earth Sci, 58(4): 491–501

Yang Z Y, Zhang S X, Yang J D et al., 2000. Stratigraphy of China: Triassic. Beijing: Geological Publishing House. 1–139

Zhang Y Q, Chen H Y, Wei W T et al., 2016. The discovery of tuff interlayer from the Triassic Ermaying Formation in northern Hebei Province and its geological significance. Geol Bull China, 35(1): 20–26