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A new oospecies of Similifaveoloolithidae from the Xiuning Basin, Late Cretaceous of Anhui, China

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ABSTRACT

Well-preserved dinosaur eggs from the Cretaceous Huizhou Formation in the Xiuning Basin, Anhui Province, China, are analysed in this paper. We describe a new oospecies, *Similifaveoloolithus qiyunshanensis,* based on several distinct characters of external morphology, size, eggshell thickness, and internal microstructure. Radial sections of this new oospecies show branched eggshell units with a fused layer near the outer surface, while numerous irregular pores and cones constitute a honeycomb pattern in tangential sections. The discovery of *S. qiyunshanensis* expands the distribution of Similifaveoloolithidae dinosaur eggs in China and provides new fossils for researching dinosaur eggshell formation mechanisms which are different from those of the currently known oofamilies. The dinosaur-egg-bearing strata in the Huizhou Formation have been dated to the early Late Cretaceous (Cenomanian-Turonian) on the basis of a similar dinosaur egg assemblage in the Tiantai Basin in Zhejiang Province. The eggs described in this paper are thought to have been laid in a buried nest while enrichment of trace elements in eggshells may have been caused by their ingestion into the body of the dinosaur producer. We suggest that the paleoclimate of this habitat was semi-arid to arid and that this environment was favourable for the preservation of eggs.

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Dinosaur egg; *Similifaveoloolithus qiyunshanensis*; Huizhou Formation; Early Late Cretaceous; Xiuning Basin, Anhui, China

Introduction

More than 200 dinosaur egg and eggshell localities have been reported from Upper Jurassic to Upper Cretaceous continental sediments in Mongolia, Korea, India, North America, South America, Europe, African, and China although none are known as yet from Antarctica and Oceania (Carpenter & Alf 1994; Vianey-Liaud & Lopez-Martinez 1997; Mohabey 1998; Grellet-Tinner et al. 2004, 2006; Agnolin et al. 2012). The earliest records of these kinds of egg fossils to be described were fragments from Southern France that were noted by Jean-Jacques Pouech in 1859 (Buffetaut & Le Loeuff 1994). Recent scientific attention on dinosaur eggs has been focused mostly on morphology and taxonomy (Buckman1859; Grigorescu et al. 2010; Sellés et al. 2013; Tanaka et al. 2016), paleoethology (Grellet-Tinner et al. 2006; Liang et al. 2009), geochemistry and paleoenvironments (Sarkar et al. 1991; Zhao et al. 2002; Kim et al. 2009; Bojar et al. 2010; Montanari et al. 2013; Riera et al. 2013), biostratigraphy and biochronology (Garcia & Vianey-Liaud 2001; Li et al. 2009; Chassagne-Manoukian et al. 2013), and taphonomy (Jackson et al. 2013).

Dinosaur eggs and eggshell fragments are numerous and widely distributed in Cretaceous continental depositional basins across China. At present, 14 oofamilies, 33 oogenera, and 70 oospecies have been described (Jin et al. 2013; Wang, Huang, et al. 2013; Zhang et al. 2014; Zhao et al. 2015; Hao et al. 2016; Xie et al. 2016), including large numbers of fossil eggs from the Laiyang Basin in Shandong Province, the Nanxiong and Heyuan basins in Guangdong Province, the Xixia Basin in Henan Province, and the Tiantai Basin in Zhejiang Province (Zhao & Jiang 1974; Zhao et al. 2002; Li et al. 2009; Tanaka et al. 2012; Wang, Zhao, et al. 2013). Although Cretaceous deposits within the Xiuning Basin have recently been recognised as fossiliferous and have yielded abundant dinosaur eggs, systematic descriptions of these fossils are in their infancy compared to other parts of China. Nevertheless, since the late 1990s, a number of oospecies have been reported, including ?*Ovaloolithus weiqiaoensis*, *Parafaveoolithus xiuningensis,* and *Wannanoolithus huangshanensis* (Yu 1998; Wang et al. 2013). The first of these has been considered of uncertain status due to the lack of microstructural images (Zhao et al. 2015), while detailed taxonomic analyses have yet to be carried out for the other two oospecies. Recently, Zhangwei and Huyi discovered new dinosaur eggs close to the northern border of Qiyunshan district within the Xiuning Basin (Figure 1) which provide further materials on which to base conclusions about geological age. In this paper, we provide the first description of these dinosaur eggs and present a preliminary discussion of biostratigraphy, paleoethology, and paleoenvironment.

*Institutional and location abbreviations***:** QYSM, Qiyunshan Geological Museum, Anhui, China; IVPP, Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, Beijing, China; PLM, polarised light microscope.

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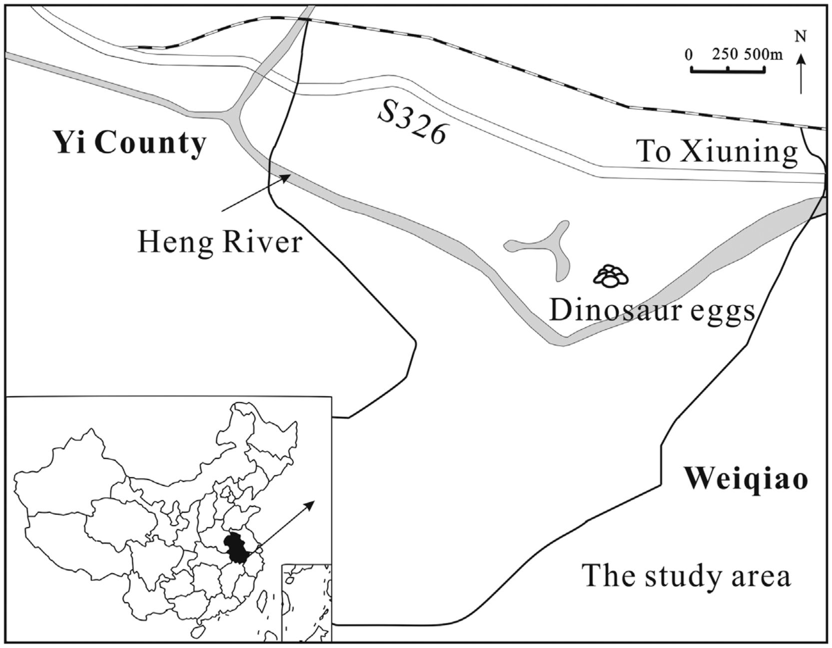

Figure 1. Map showing the location of Similifaveoloolithid eggs in Qiyunshan area, Anhui Province, China. Source: Modified from Xing et al. 2014.

Geological setting

The dinosaur-egg-bearing site discussed in this paper lies on the margin of the Qiyunshan scenic area, Xiuning County, within the city of Huangshan in Anhui Province in the northwestern region of the Cretaceous Xiuning Basin. Regional geological survey results suggest that the Xiuning Basin is a typical small Mesozoic intermontane basin in eastern China that is bounded by a series of northeast (NE) and north-northeast (NNE) trending faults (Yu & Wang 2001). Typical Danxia landforms characterised by different peaks in southeastern China as well as Cretaceous-aged red beds are well-developed within the Qiyunshan syncline structure of the Xiuning Basin and are divided into three ascending stratigraphic units, the Huizhou, Qiyunshan, and Xiaoyan formations. These rocks are overlain by Mesoproterozoic strata and underlain by Quaternary deposits (No. 322 Geological Team, Bureau of Geology & Mineral Exploration of Anhui Province 2001). Field work has shown that most of the outcrops containing dinosaur remains are associated with the Xiaoyan and Huizhou formations, while skeletons of the pachycephalosaur *Wannanosaurus yansiensis* as well as theropod tracks referred to *Paracorpulentapus zhangsanfengi* have been collected from the upper part of the Xiaoyan Formation (Yu 1998; Butler & Zhao 2009; Xing et al. 2014).

Outcrops of the Huizhou Formation are the main constituents of the Xiuning Mesozoic red bed Basin, which is approximately 785 m thick and is characterised by red sandstones, mudstones, and conglomerates that contain diverse assemblages of dinosaur bones, tracks, and eggs. The Huizhou Formation is further divided into lower and upper members; of these, the upper member is a cyclic sequence composed of purple and thick layers of sandstone and siltstones with interlayers of silty mudstones that reaches a maximum thickness of 371.4 m, while the lower member is a sedimentary sequence comprised of red conglomerates and silty mudstones mixed with lithic sandstones and siltstones that has a total thickness of 413.2 m. The dinosaur bone site for *Xiuningpus xintanensis* occurs in a bentonite layer towards the lowermost part of the basal member, while known Shangshangen footprints are preserved in a thin-layered mudstone unit, located stratigraphically in the upper part of the upper member (Yu 1998). The purple-red lithic sandstone from the upper part of upper member has yielded the majority of egg fossils including ?*Ovaloolithus weiqiaoensis* as well as new material of *Parafaveoolithus xiuningensis* and *Wannanoolithus huangshanensis* (Yu 1999; No. 322 Geological Team, Bureau of Geology & Mineral Exploration of Anhui Province 2001). The newly discovered dinosaur egg sites reported here are exposed in fine grained reddish and thickly-bedded sandstone layers in the uppermost part of the upper member of the Huizhou Formation (Figure 2).

Materials and methods

In order to prevent weathering, all the dinosaur eggs reported in this paper are housed in the QYSM. A total of ca. 20 eggshell fragments were collected from three of the best-preserved eggs (QYSM-1, QYSM-2, QYSM-3) during field investigations, and four or five fragments from each were examined in this study. Laboratory preparation and microstructural observations were performed at the IVPP; preparation work included cleaning samples with hydroxide peroxide in an ultrasonic bath and drying in a heating chamber at 50° which made it simple to remove the loose sediment from the fragments with a small needle. Least weathered eggshells were then selected for examination; eggshell thickness was measured multiple times from thin section images, and samples were embedded in EXAKT Technovit 7200 one-component resin and cut with an EXAKT 300CP automatic microtome. Radial and tangential sections were then prepared by grinding and polishing to a thickness of approximately 40 μm using an EXAKT 400CP variable speed grinder-polisher with P1200 and P4000 abrasive paper. Sections were viewed under normal and polarized light using a Zeiss Axio Imager A2 PLM.

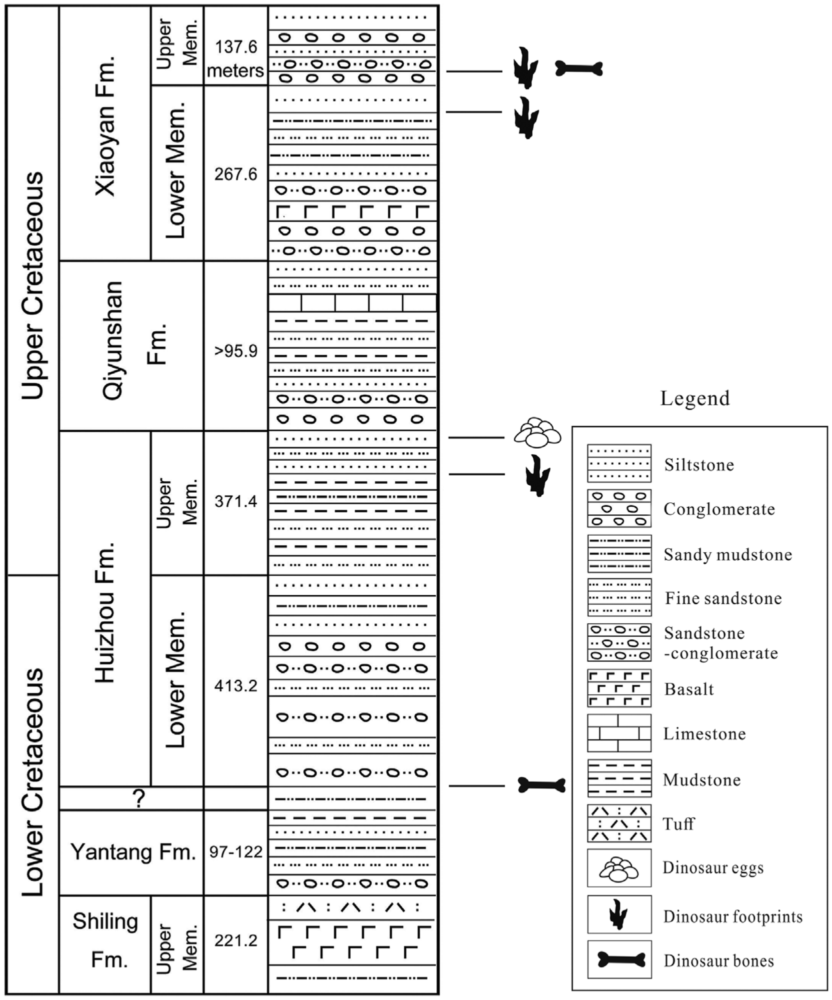

Figure 2. Stratigraphic section of the Cretaceous strata in the Xiuning Basin with the position of the eggs described herein (emended from Yu & Wang 2001; Xing et al. 2014).

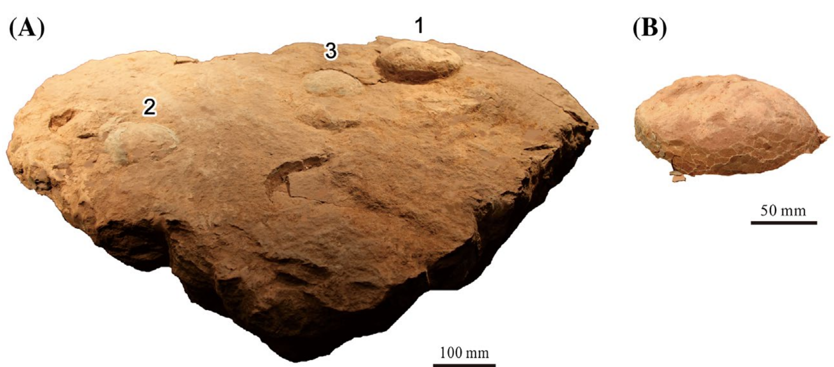

Figure 3. Holotype of *Similifaveoloolithus qiyunshanensis* oosp. nov.
Note: (A) A clutch containing about 10 eggs; (B) Holotype of QYSM-1.

Three tangential sections were selected for observations; All eggshell thin sections are catalogued at IVPP and were identified using the parataxonomy outlined by Zhao et al. (2015).

Systematic paleontology

Oofamily. Similifaveoloolithidae Wang, Zhao, Wang et Jiang, 2011

Oogenus. *Similifaveoloolithus* Wang, Zhao, Wang et Jiang, 2011

Oospecies. *Similifaveoloolithus qiyunshanensis* oosp. nov. (Figure 3, 4)

Etymology. 'Qiyunshan' for the dinosaur egg locality within the Xiuning Basin, Anhui Province, China.

Holotype. A nest composed of ca. ten eggs, of which three are relatively complete (QYSM-1, QYSM-2, QYSM-3) as well as

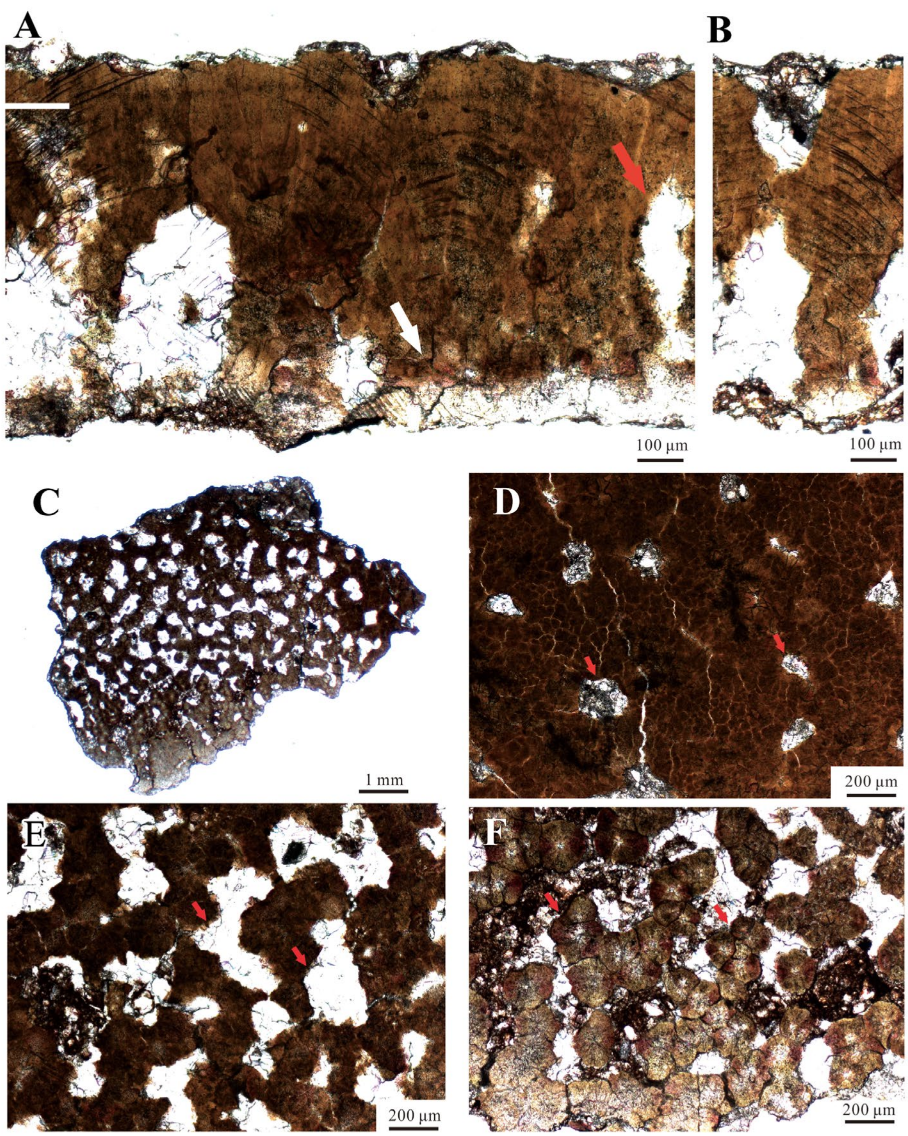

Figure 4. Eggshell microstructure of *Similifaveoloolithus qiyunshanensis*.

Notes: (A) Radial section through the eggshell under PLM, showing irregular pore channels and cones. Red arrows point to the situation of pore channels, while white point to cones; (B) Radial section through the eggshell under PLM, showing branched eggshell units. (C) honeycomb structure of the whole eggshell in the middle part of tangential section; (D) tangential section near the outer surface of eggshell, showing the fused eggshell units and the irregular pores. Red arrows point to the situation of pores; (E) tangential section through the middle part of eggshell, showing interconnected eggshell units and connected pores. Red arrows point to the situation of pores; (F) tangential section near the inner surface of eggshell, showing isolated eggshell units and tightly arranged cones. Red arrows point to the situation of cones.

seven broken eggs, all preserved in QYSM (Figure 3). QYSM-1 is the most complete egg while QYSM-2 and QYSM-3 are exposed just in part.

Type locality and horizon. The uppermost section of the upper member of the Huizhou Formation, Late Cretaceous, Qiyunshan Town, Xiuning County, Anhui Province, China.

Diagnosis. The eggshell is composed of columnar, or asymmetric, branched units that are irregular in shape in radial section. Eggshell units are tightly fused near the outer surface of the eggshell, and the pore canals are extremely numerous and irregular, forming a honeycomb organisation when viewed tangential section from the middle of shell (Figure 4).

Description. All eggs are sub-ellipsoidal and are irregularly arranged in the nest. The polar axis and equatorial diameter of QYSM-1 are 135 and 96 mm, respectively, while measurements of QYSM-2 and QYSM-3 could not be accurately performed

Table 1. Measurements of *Similifaveoloolithus qiyunshanensis* oosp. nov.

Egg number	Polar axis (mm)	Equatorial diameter (mm)	Shape index
QYSM-1	135	96	71.1
QYSM-2	110+	83+	75.4
QYSM-3	109+	75+	68.8

(Table 1). Eggshell thicknesses range between 0.74 and 0.97 mm (average: 0.86 mm), and the outer surfaces of eggshells exhibit short surface ornaments or protuberances, as well as an abundance of pore canals.

Eggshells comprise a single structural layer in radial section and reticular units are invisible. Polygonal, or circular, cones on the inner surface of eggshells exhibit a red layered structure under PLM, separated by surrounding canal openings. The units in the mid-lower portions of the shell are columnar or

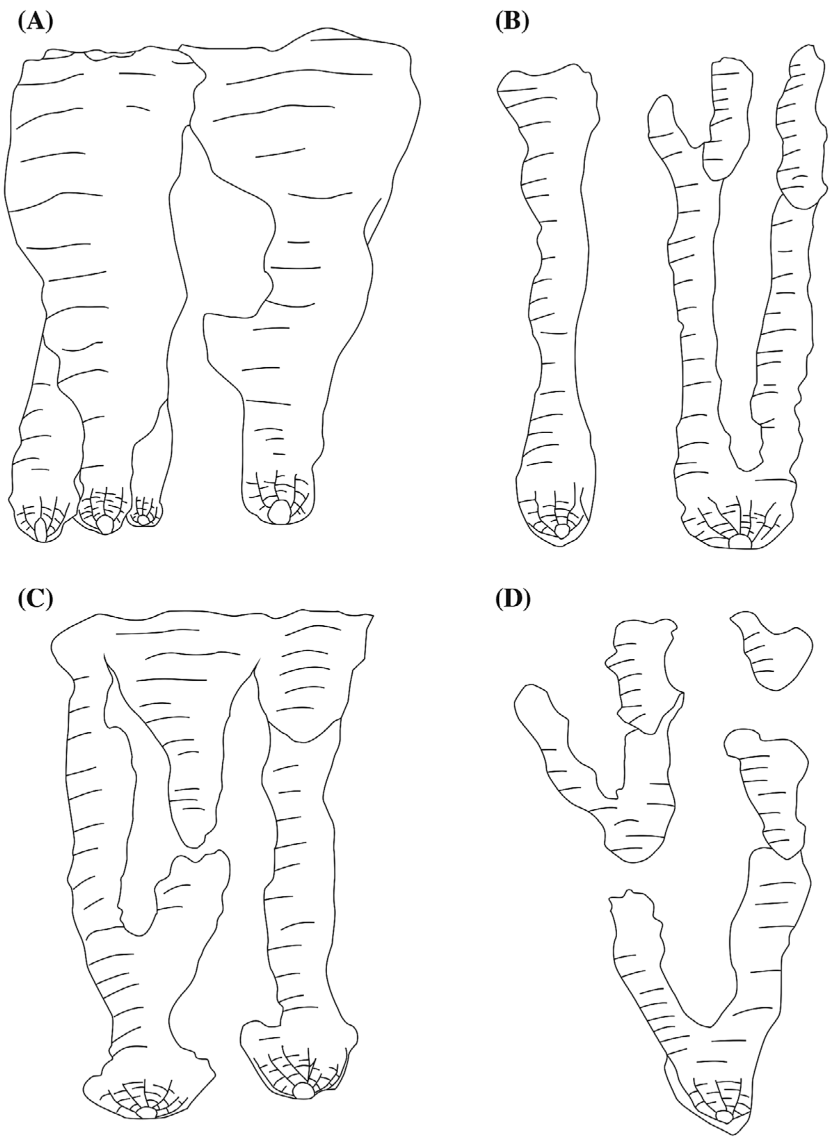

Figure 5. A line drawing shows the distinctions of eggshell units in radial section among Similifaveoloolithidae, Faveoloolithidae, Dendroolithidae, and Dictyoolithidae.
Notes: (A) Similifaveoloolithidae, showing a single structural layer without 'reticular' shell units; (B) Faveoloolithidae, (C) Dendroolithidae, (D) Dityoolithidae, showing relatively irregular 'reticular' eggshell units.

have few branches above cones; large and irregular pore channels between eggshell units are well-developed, ranging between 79 and 247 μm in width. These canals would have enabled the exchange of gases and water vapor through shell. Most observed pore canals are closed off and the shell units are tightly arranged forming a fused layer beneath the outer surface. The height of this fused layer ranges between one fifth and one sixth of the total eggshell thickness.

Tangential sections of eggshell units reveal honeycomb-like structures with large and rimiform pore canals, which vary considerably in shape. Adjacent to the inner surface, eggshell units are divided by irregular pore canals that exhibit sinuous tubes connections between them; compared to the pores, the cones (calcite nuclei) of eggshells can be recognised; the geometry and size of these structures are different from one another, as most are subspherical with diameters between 0.05 and 0.23 mm (average: 0.14 mm) and there are about 34 cones per square millimetre. Through the middle part of the eggshell, neighbouring pores coalesce into larger and branching structures that have variable diameters along the pore length (between 0.04 and 0.55 mm at an average of nine pores /mm^2). In the upper portion of the eggshell, most eggshell unit branches fuse with adjacent ones and a large number of pores are closed, which means that both the number and diameter of these structures decreases significantly. Pore diameters vary between 0.02 and 0.20 mm and are subcircular or triangular in shape. Calculated pore density is 6 pores/mm^2.

Comparison. The QYSM eggs we studied are ellipsoid in shape and exhibit eggshell microstructures comprising one irregular layer unit that is different from other oofamilies, including Macroelongatoolithidae, Elongatoolithidae, and Prismatoolithidae which all contain regular units of two layers including an upper columnar and lower mammillary layers (Tanaka et al. 2011; Wang Q et al. 2012). Numerous irregular pore canals and branched eggshell units are developed in the QYSM fossils, features that differ significantly from Ovaloolithidae, Megaloolithidae, Spheroolithidae, and Stalicoolithidae, but resemble Faveoloolithidae, Dendroolithidae, and Dictyoolithidae (Zhao et al. 2015).

The QYSM eggshells most closely resemble those of Faveoloolithidae, although comprising a single shell unit in radial section that lacks reticular units of irregular shape. Although all of these shells are remarkable for their honeycomb-like structure in tangential section, the QYSM specimens exhibit more irregular and rimiform pore canals which connect to each other forming curved shape. A further significant difference between these shells is that the thickness of the new shells is thinner than known eggs referred to Faveoloolithidae, and compared to Dendroolithidae and Dictyoolithidae, branching eggshell units and compact layer near the outer surface in radial section are also developed. Dendritic and reticulate eggshell units are not seen in the QYSM eggshell (Figure 5); on the basis of macrostructure, microstructures, and nesting characteristics, these eggs can be assigned with confidence to Similifaveoloolithidae (Wang et al. 2011).

At the moment, just one oogenus, *Similifaveoloolithus,* has been referred to Similifaveoloolithidae and their characteristics are consistent. Two oospecies, *S. shuangtangensis* and *S. gongzhulingensis*, were erected by Wang (2011, 2013); the Qiyunshan specimens share several characteristics with the typical oospecies *S. shuangtangensis* from the Chichengshan Formation in Zhejiang Province, including the presence of extremely numerous irregular pores, and irregular branched eggshell units. However, the QYSM eggs also exhibit some traits that distinguish them from *S. shuangtangensis*; these eggshells are thinner than those of *S. shuangtangensis* which range between 1.05 and 1.20 mm, and the compact layer near to the outer surface of the eggshell is also thinner in these new shells. Cones near the inner surface of the Qiyunshan eggshell in tangential view, as well as columnar eggshell units in radial views, are better developed compared with the *S. shuangtangensis* specimens. In addition, the difference between these eggs and *S. gongzhulingensis* is also remarkable in terms of eggshell thickness (between 1.40 and 1.70 mm in *S. gongzhulingensis*), radial section microstructure, and the fused eggshell units beneath the outer surface of the shell. The QYSM eggs are also easily distinguished from other oospecies in general external shape and size; thus, these specimens are referred to the new oospecies, *Similifaveoloolithus qiyunshanensis*.

Discussion. Dinosaur eggshells are classified into a number of relatively primitive ootaxa including dictyoolithids, faveoloolithids, dendroolithids, as well as relatively advanced ootaxa including elongatoolithids and prismatoolithids (Zhao 1993). Primitive examples exhibit complete extinction patterns including reticular eggshell units and well-developed pore canals, whereas the latter have some similarities with extant crocodilians and avians based on their non-reticular eggshell units and narrow pore canals (Zhao et al. 2015). Similifaveoloolithidae has well-developed pore canals, but no reticular eggshell units under PLM. Therefore, it is very important in the process of the evolution of dinosaur eggs. Similifaveoloolithidae is a new oofamily worldwide only reported in Zhejiang and Jilin Province, China. So *Similifaveoloolithus qiyunshanensis* reported here is the first record in Anhui Province, China. These fossils expand our knowledge of the diversity of Cretaceous egg fossils in Southern Anhui and China, but also provide new fossils for the study of dinosaur eggshell formation mechanism.

The age of the QYSM egg-bearing sediments remains controversial because of the lack of chronostratigraphic data for the Huizhou Formation in the Xiuning Basin. A 1:50,000 scale regional geological survey of Jurassic-Cretaceous rocks within the Xiuning Basin of the Huangshan area shows that these sediments belong to the late Early Cretaceous. Yu (1998) studied the fossil-bearing red deposits of the Huizhou Formation and divided them into two periods such that the lower part belongs to the late Early Cretaceous while the upper part belongs to the early Late Cretaceous. Recently, Ren et al. (2016) considered that the late Early Cretaceous Xintan Formation should be re-established as the result of a regional geological survey in the Tunxi-Xiuning area, and that the overlying strata Huizhou Formation should be re-assigned to the early Late Cretaceous.

The ages of 90% of the known dinosaur-egg-bearing layers are predominantly restricted to Cretaceous deposits (Paik et al. 2012), besides occurrences in the Late Triassic in South America (Bonaparte & Vince 1979) as well as the Jurassic in America, Europe, India, and South America (Hirsch et al. 1989; Weishampel et al. 2004). In China, all the 41 known dinosaur egg sites have been found in Cretaceous strata, with just three localities known from the Early Cretaceous (Zhao & Zhao 1999; Wang et al. 2015; Zhao et al. 2015; Xie et al. 2016). Thus, eggs and eggshell fragments provide reliable biochronological markers for both the division and correlation of Cretaceous continental red beds while others are relatively less important; eggs and eggshells occur at great abundance, have great variety, excellent preservation, a wide distribution, and have a large stratigraphic coverage (Vianey-Liaud et al. 1994; Garcia & Vianey-Liaud 2001; He et al. 2013). In other words, confirming the kind of dinosaur eggs and their associated faunas within the Qiyunshan area of the Xiuning Basin will help us to ascertain their age and resolve the controversy of the Huizhou Formation.

On the basis of preliminary statistics, we know that the Xiuning Basin is currently dominated by two oofamilies (i.e. Faveoloolithidae: *Parafaveoolithus xiuningensis*; Similifaveoloolithidae: *Similifaveoloolithus qiyunshanensis*) which both have well-developed pore canals, as well as shells referred to as *incertae sedis* (i.e. *Wannanoolithus huangshanensis* and ?*Ovaloolithus weiqiaoensis*) (Yu 1998; Wang, Huang, et al. 2013). Thus, compared to other dinosaur egg assemblages from major Chinese basins that exhibit great diversity and abundance, including the Laiyang, Nanxiong, Xixia, and Tiantai basins (Zhao & Jiang 1974; Zhao et al. 2002; Li et al. 2009; Wang et al. 2010), the dinosaur egg fauna from the Xiuning Basin most closely resembles that from the Tiantai Basin which is dominated by Faveoloolithidae, Dictyoolithidae, and Spheroolithidae, but lacking Ovaloolithidae (Fang et al. 2000, 2003; Wang et al. 2011; Wang, Zhao, et al. 2013; Barta et al. 2014). The Tiantai dinosaur egg fauna is early Late Cretaceous in age (Jiang et al. 2011), while SIMS zircon U-Pb ages from the dinosaur egg-bearing deposits of the Laijia and Chichengshan formations within the Tiantai Basin range in age between 96 and 99 Ma (Cenomanian) and 91 and 94 Ma (Turonian) (He et al. 2013), consistent with the preliminary time framework for the dinosaur egg strata from the Tiantai, Laiyang, Xixia, and Nanxiong basins (Wang XL et al. 2012). There is therefore a strong possibility that the geological age of the dinosaur egg-bearing strata within the Xiuning Basin is early Late Cretaceous (Ren et al. 2016).

Table 2. The content of elements in the dinosaur eggshells.

	Macroelements							Trace elements						
	Content (10^{-6} g/g)													10^{-12} g/g
Sample	Ca	Na	Mg	K	Fe	Al	Sr	As	Pb	Mn	Cr	La	U	Ir
Eggshells	56,798.8	1501.6	5452.7	4790.5	5314.2	9795.2	6526.9	116.3	12.1	1313.0	10.5	9.0	1.1	41.6
Surrounding rocks	10,978.2	7295.8	6209.1	23,934.8	27,053	46,555	305.5	62	14.9	492.7	35.2	18.3	1.8	230.4

Note: The content of elements is the average of QYSM-1, QYSM-2 and QYSM-3.

Paleoethology and paleoenvironment

The nesting environments of Cretaceous dinosaurs globally come from a range of diverse depositional conditions encompassing inland to littoral areas although the major habitat comprised inland floodplains and alluvial fans (Paik et al. 2004; Díaz-Molina et al. 2007). The absence of marine fossils in the Xiuning Basin indicates a continental origin while the lithological features of Qiyunshan dinosaur-egg-bearing units are dominated by fine-grained lithic sandstones interbedded with silty mudstones, interpreted as a small fan delta-deep lacustrine deposit (Yu & Wang 2001). The absence of significant lithological changes from egg-bearing sediments to overlying layers mirrors the fact that dinosaurs preferred stable sedimentary environments for nesting.

The nesting behaviour of dinosaurs contributes to the preservation of their eggs. The spatial arrangement of eggs can be classified into four modes, radial, irregular, multi-bed parallel, and cross-parallel (Zhou et al. 2001). *Similifaveoloolithus qiyunshanensis* eggs are arranged irregularly based on cross modes and the diverse distance between eggs between 5 and 44 cm. All of these examples are characterised by developed pores, the channels for material exchange between buried nests and outer spaces, while the highest pore density of tangential sections is ca. 15 per square millimeter. Because of their irregular arrangement and the highly porous nature of eggs, it is highly probable that the Qiyunshan dinosaurs laid their eggs in buried nests during incubation represented by Spheroolithidae and Faveoloolithidae (Zhao 1979). These fossils occur commonly in sandstones or silty mudstone layers in close accord with Sanlimiao eggs from the Xixia Basin (Liang et al. 2009). In general, the ways that eggs are buried in nests within fine-grained sediments as autochthonous type (Liang et al. 2009; Paik et al. 2012). According to this observation, the integrity of eggs was partly maintained and egg bodies were destroyed in some degree. For example, the absence of surrounding rock and eggshell on the right side of the QYSM-1 is obvious (Figure 3). It is assumed that Qiyunshan dinosaur eggs were outcropped by weathering for a period of time.

In order to understand the living environment of dinosaur fauna and the reason of hatchability reduction, the content of the main and trace elements of Qiyunshan eggshell and surrounding rock samples were analysed by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) in modern testing centre of Anhui University. For the sake of avoiding secondary alterations influence on the original chemical composition of eggshell, the eggshell debris which is not filled with secondary calcite is tested. In addition, there are no recrystallization and diagenetic alteration under PLM. So the experimental content of the eggshell is the true composition of Qiyunshan dinosaur eggshells.

Results reveal that the eggshell mainly consists of macroelements such as Ca, Na, Mg, K, Fe, Al and other trace elements such as Sr, As, Pb, Mn, Cr, La, U, Ir (Table 2). Trace elementary combinations are featured by high Sr and Ir (6,526.9 × 10^{-6} g/g, and average 41.6 × 10^{-12} g/g respectively), and other harmful elements such as As, Pb, Mn, Cr, etc. Especially, the content of Ir is relatively high compared with most of the CGN section of Nanxiong Basin (Zhao et al. 2009), and obviously higher than that of Xixia Basin (average 9.3 × 10^{-12} g/g, respectively) (Wang et al. 2015). It is speculated that excess of trace elements in eggshells were caused by the ingestion of them into the dinosaur body, and then into the eggs (Zhao et al. 2002, 2009; Zhang & Pei 2004). However, the high concentration of trace elements has no effect on the eggshell structure in the light of eggshell microstructure characteristics of QYSM eggs. On the other hand, deficiency of organic elements (such as C, N, P, S) and trace elements (such as La, U) may be related to the low content of organic matter of sedimentary environment, which conform to the conclusion that high organic content resulting in low pH is a negative factor for the preservation of eggs (Paik et al. 2012). The content of essential elements Fe reaches up to 5314.2 × 10^{-6} g/g, indicating the paleoclimate of the nesting site was semi-arid to arid during the Late Cretaceous that is unfavorable to the dinosaur diversity (Zhao et al. 2013). The semi-arid to arid paleoclimate is also the cause of the formation of intermittent flood which results in alluvial fan floodplains. Repeated flooding events can be a positive condition for the rapid burial and preservation of eggs. Meanwhile, compared with ordinary sedimentary rock, the sharp increase of Fe in eggshell debris and surrounding rocks are directly related to the Cretaceous red bed and the typical Danxia landforms of Southeast China.

Conclusions

(1) The QYSM dinosaur eggs from the Xiuning Basin, China, are assigned here to the new oospecies *Similifaveoloolithus qiyunshanensis* because of their ellipsoidal shape, relatively thinner eggshell thickness (between 0.74 and 0.97 mm), columnar eggshell units with a compact layer near the outer surface, and the majority of irregular pores and cones in tangential sections.

(2) The Xiuning Basin dinosaur egg fauna represents two oofamilies (Similifaveoloolithidae and Faveoloolithidae) and resembles those found in the Tiantai Basin. The age of QYSM fossil-bearing strata could be the early Late Cretaceous on the basis of reliable isotopic ages from the Tiantai Basin, which

corresponds to the newly regional geological survey results in the Tunxi-Xiuning area (Ren et al. 2016).

(3) The QYSM eggs could be speculated laid via burial nesting on the basis of the spatial arrangement and the highly porous nature of eggs, and the lithological features. The high concentration of trace elements in eggshells may have been caused by receiving polluted diets during the life of dinosaurs, and the habitat was dominated by a semi-arid to arid climate in the early Late Cretaceous of the Xiuning Basin.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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References

Agnolin FL, Powell JE, Novas FE, Kundrát M. 2012. New alvarezsaurid (Dinosauria, Theropoda) from uppermost Cretaceous of north-western Patagonia with associated eggs. Cretac Res. 35:33–56.

Barta DE, Brundridge KM, Croghan JA, Jackson FD, Varricchio DJ, Jin X, Poust AW. 2014. Eggs and clutches of the Spheroolithidae from the Cretaceous Tiantai basin, Zhejiang Province, China. Hist Biol. 26(2):183–194.

Bojar A, Csiki Z, Grigorescu D. 2010. Stable isotope distribution in Maastrichtian vertebrates and paleosols from the Haţeg Basin, South Carpathians. Palaeogeogr Palaeoclimatol Palaeoecol. 293:329–342.

Bonaparte JF, Vince M. 1979. El hallazgo del primer nido de dinosaurios Triasicos (Saurischia Prosauropoda), Triasicos superior de Patagonia, Argentina [Discovery of The first nest of Triassic dinosaurs (Saurischia, Prosauropoda) from the Upper Triassic of Patagonia]. Ameghniaana. 16:173–182.

Buckman J. 1859. On some fossil reptilian eggs from the Great Oolite of Chirencester. Quart J Geol Soc London. 16:107–110.

Buffetaut E, Le Loeuff J. 1994. The discovery of dinosaur eggshells in nineteenth-century France. In: Carpenter K, Hirsch KF, Horner JR, editors. Dinosaur eggs and babies. New York (NY): Cambridge University Press; p. 31–34.

Butler RJ, Zhao Q. 2009. The small-bodied ornithischian dinosaurs *Micropachycephalosaurus hongtuyanensis* and *Wannanosaurus yansiensis* from the Late Cretaceous of China. Cretac Res. 30:63–77.

Carpenter KA, Alf K. 1994. Global distribution of dinosaur eggs, nests, and babies. In: Carpenter K, Hirsch KF, Horner JR, editors. Dinosaur eggs and babies. New York (NY): Cambridge University Press; p. 15–30.

Chassagne-Manoukian M, Haddoumi H, Cappetta H, Charrière A, Feist M, Tabuce R, Vianey-Liaud M. 2013. Dating the "red beds" of the Eastern Moroccan High Plateaus: evidence from late Late Cretaceous charophytes and dinosaur eggshells. Geobios. 46:371–379.

Díaz-Molina M, Kälin O, Benito MI, Lopez-Martinez N, Vicens E. 2007. Depositional setting and early diagenesis of the dinosaur eggshell-bearing Aren Fm at Bastus, Late Campanian, south-central Pyrenees. Sed Geol. 199:205–221.

Fang X, Lu L, Jiang Y, Yang L. 2003. Cretaceous fossil eggs from the Tiantai basin of Zhejiang, with a discussion on the extinction of dinosaurs. Geol Bull China. 22(7):512–520.

Fang X, Wang Y, Jiang Y. 2000. On the Late Cretaceous fossil eggs of Tiantai, Zhejiang. Geol Rev. 46(1):105–112.

Garcia G, Vianey-Liaud M. 2001. Dinosaur eggshells as biochronological markers in Upper Cretaceous continental deposits. Palaeogeogr Palaeoclimatol Palaeoecol. 169:153–164.

Grellet-Tinner G, Chiappe L, Coria R. 2004. Eggs of titanosaurid sauropods from the Upper Cretaceous of Auca Mahuevo (Argentina). Can J Earth Sci. 41(8):949–960.

Grellet-Tinner G, Chiappe L, Norell M, Bottjer D. 2006. Dinosaur eggs and nesting behaviors: a paleobiological investigation. Palaeogeogr Palaeoclimatol Palaeoecol. 232:294–321.

Grigorescu D, Garcia G, Csiki Z, Codrea V, Bojar A. 2010. Uppermost Cretaceous megaloolithid eggs from the Haţeg Basin, Romania, associated with hadrosaur hatchlings: search for explanation. Palaeogeogr Palaeoclimatol Palaeoecol. 293:360–374.

Hao ZG, Fei HC, Hao QQ, Liu L. 2016. Distribution and characteristics of dinosaur eggs in China. Acta Geol Sin (English Ed). 90(1):370–375.

He HY, Wang XL, Wang Q, Jiang SX, Cheng X, Zhang JL, Zhou ZH, Zhao ZK, Jiang YG, Yu FM, et al. 2013. SIMS zircon U-Pb dating of the Late Cretaceous dinosaur egg-bearing red deposits in the Tiantai Basin, southeastern China. J Asian Earth Sci. 62:654–661.

Hirsch KF, Stadtman KL, Miller WE, Madsen JH Jr. 1989. Upper Jurassic dinosaur egg from Utah. Science. 243:1711–1713.

Jackson FD, Schmitt JG, Oser SE. 2013. Influence of Vertisol development on sauropod egg taphonomy and distribution at the Auca Mahuevo locality, Patagonia, Argentina. Palaeogeogr Palaeoclimatol Palaeoecol. 386:300–307.

Jiang Y, Qian MP, Chen R, Jiang YG, Zhang YJ, Xing GF. 2011. The Cretaceous dinosaur fossil strata of the Tiantai Basin, Zhejiang Province. J Stratigr. 35(3):258–267. Chinese with English Abstract.

Jin XS, Zheng WJ, Xie JF, Chen RJ. 2013. The dinosaur fossils from Dongyang, Zhejiang Province. In: Abstract Volume, The 11th National Congress of the Palaeontological Society of China (PSC) and The 27th Annual Conference of PSC; Dongyang. p. 170–171. Chinese.

Kim C, Al-Aasm IS, Ghazban F, Chang H. 2009. Stable isotopic composition of dinosaur eggshells and pedogenic carbonates in the upper cretaceous seonso formation, South Korea: Paleoenvironmental and diagenetic implications. Cretac Res. 30:93–99.

Li G, Chen PJ, Wang DY, Batten DJ. 2009. The spinicaudatan Tylestheria and biostratigraphic significance for the age of dinosaur eggs in the Upper Cretaceous Majiacun Formation, Xixia Basin, Henan Province, China. Cretac Res. 30:477–482.

Liang XQ, Wen SN, Yang DS, Zhou SQ, Wu SC. 2009. Dinosaur eggs and dinosaur egg-bearing deposits (Upper Cretaceous) of Henan Province, China: occurrences, palaeoenvironments, taphonomy and preservation. Prog Nat Sci. 19:1587–1601.

Mohabey DM. 1998. Systematics of Indian Upper Cretaceous dinosaur and chelonian eggshells. J Vertebr Paleontol. 18:348–362.

Montanari S, Higgins P, Norell MA. 2013. Dinosaur eggshell and tooth enamel geochemistry as an indicator of Mongolian Late Cretaceous paleoenvironments. Palaeogeogr Palaeoclimatol Palaeoecol. 370:158–166.

No. 322 Geological Team, Bureau of Geology and Mineral Exploration of Anhui Province. 2001. A comprehensive report of Qiyun Mountain National Geopark in Anhui Province. Hefei City, internal publication. 48p.

Paik IS, Huh M, Kim HJ. 2004. Dinosaur egg-bearing deposits (Upper Cretaceous) of Boseong, Korea: occurrence, palaeoenvironments, taphonomy, and preservation. Palaeogeogr Palaeoclimatol Palaeoecol. 205:155–168.

Paik IS, Kim HJ, Huh M. 2012. Dinosaur egg deposits in the Cretaceous Gyeongsang Supergroup, Korea: Diversity and paleobiological implications. J Asian Earth Sci. 56:135–146.

Ren XX, Huang JD, Liu J, Bi ZG. 2016. New understanding of the Xintan Formation in late Early Cretaceous in South Anhui. Geol Anhui. 26(3):175–178. Chinese with English Abstract.

Riera V, Anadón P, Oms O, Estrada R, Maestro E. 2013. Dinosaur eggshell isotope geochemistry as tools of palaeoenvironmental reconstruction for the upper Cretaceous from the Tremp Formation (Southern Pyrenees). Sed Geol. 294:356–370.

Sarkar A, Bhattacharya SK, Mohabey DM. 1991. Stable-isotope analyses of dinosaur eggshells: paleoenvironmental implications. Geology. 19(11):1068–1071.

Sellés AG, Bravon AM, Delclòs X, Colombo F, Martí X, Ortega-Blanco J, Parellada C, Galobart À. 2013. Dinosaur eggs in the Upper Cretaceous of the Coll de Nargó area, Lleida Province, south-central Pyrenees, Spain: oodiversity, biostratigraphy and their implications. Cretac Res. 40:10–20.

Tanaka K, Lü J, Kobayashi Y, Zelenitsky DK, Xu L, Jia SH, Qin S, Tang MA. 2011. Description and phylogenetic position of dinosaur eggshells from the Luanchuan area of Western Henan Province, China. Acta Geol Sin – Eng Ed. 85(1):66–74.

Tanaka K, Junchang Lü, Liu Y, Huang ZQ, Kobayashi Y, Huang D, Zelenitsky DK. 2012. Statistical approach for classification of dinosaur eggs from the Heyuan Basin at the Northeast of Guangdong Province. Acta Geol Sin – Eng Ed. 86(2):294–303.

Tanaka K, Zelenitsky DK, Saegusa H, Ikeda T, DeBuhr CL, Therrien F. 2016. Dinosaur eggshell assemblage from Japan reveals unknown diversity of small theropods. Cretac Res. 57:350–363.

Vianey-Liaud M, Lopez-Martinez N. 1997. Late Cretaceous dinosaur eggshells from the Tremp Basin, southern Pyrenees, Lleida, Spain. J Paleontol. 71(6):1157–1171.

Vianey-Liaud M, Mallan P, Buscail O, Montgelard C. 1994. Review of French dinosaur eggshells: morphology, structure, mineral and organic composition. In: Carpenter K, Hirsch KF, Horner JR, editors. Dinosaur eggs and babies. New York (NY): Cambridge University Press; p. 151–183.

Wang Q, Huang JD, Wang XL, Li N, Hu YC, Ren XX. 2013. The new type of dinosaur eggs from the Upper Cretaceous of South Anhui. In: Abstract Volume, The 11th National Congress of the Palaeontological Society of China (PSC) and The 27th Annual Conference of PSC, Dongyang; p. 173. Chinese.

Wang Q, Wang XL, Zhao ZK, Jiang YG. 2012. A new oofamily of dinosaur egg from the Upper Cretaceous of Tiantai Basin, Zhejiang Province, and its mechanism of eggshell formation. Chin Sci Bull. 57(28–29):3740–3747.

Wang Q, Zhao ZK, Wang XL, Jiang YG. 2011. New ootypes of dinosaur eggs from the Late Cretaceous in Tiantai Basin, Zhejiang Province, China. Verteb PalAsiat. 49(4):446–449.

Wang Q, Zhao ZK, Wang XL, Jiang YG, Zhang SK. 2010. A new oogenus of Macroelongatoolithid eggs from the Upper Cretaceous Chichengshan Formation of the Tiantai Basin, Zhejiang Province and a revision of the Macroelongatoolithids. Acta Palaeontol Sin. 49(1):73–86.

Wang Q, Zhao ZK, Wang XL, Zhang SK, Jiang YG. 2013. New forms of dictyoolithids from the Tiantai Basin, Zhejiang Province of China and a parataxonomic revision of the dictyoolithids. Verteb PalAsiat. 51(1):43–54.

Wang XL, Wang Q, Jiang SX, Cheng X, Zhang JL, Zhao ZK, Jiang YG. 2012. Dinosaur egg faunas of the Upper Cretaceous terrestrial red beds of China and their stratigraphical significance. J Stratigr. 36(2):400–416.

Wang XW, Yao XY, Xu XY. 2015. Trace element determination of Late Cretaceous dinosaur eggshell fossils from Xixia Basin, Henan Province by ICP-OES and its implications for extinction of dinosaurs. Rock Mineral Anal. 34(5):520–527. Chinese with English Abstract.

Weishampel DB, Barrett PM, Coria RA, Loeuff JL, Xing X, Xijin Z, Sahni A, Gomani EMP, Noto CR. 2004. Dinosaur distribution. In: Weishampel DB, Dodson P, Osmólska H, editors. The Dinosauria. California: University of California Press; p. 517–606.

Xie JF, Zhang SK, Jin XS, Li DQ, Zhou LQ. 2016. A new type of dinosaur eggs from Early Cretaceous of Gansu Province, China. Verteb PalAsiat. 54(1):79–88.

Xing LD, Lockley MG, Zhang JP, Klein H, Kim JY, Persons W, Matsukawa M, Yu XQ, Li JJ, Chen GB, et al. 2014. Upper Cretaceous dinosaur track assemblages and a new theropod ichnotaxon from Anhui Province, eastern China. Cretac Res. 49:190–204.

Yu XQ. 1998. Characteristics of dinosaur fossils from Southern Anhui and their significance for stratigraphic division. Reg Geol China. 17(3):278–284. Chinese with English Abstract.

Yu XQ. 1999. The occurrence features of dinosaur's fossils in the Xiuning area, South Anhui. Geol Anhui. 9(2):94–101. Chinese with English Abstract.

Yu XQ, Wang DE. 2001. Jurassic-Cretaceous sequence stratigraphy of Huangshan area in South Anhui. Geoscience. 15(1):27–34. Chinese with English Abstract.

Zhang SK, Jin XS, O'Connor J, Wang M, Xie JF. 2014. A new egg with avian egg shape from the Upper Cretaceous of Zhejiang Province, China. Hist Biol. 27:595–602.

Zhang YG, Pei J. 2004. Trace element combinations in Upper Cretaceous dinosaur egg fossils from Xixia Basin and discussion on paleoclimate. Acta Palaeontol Sin. 43(2):297–302. Chinese with English Abstract.

Zhao H, Zhao ZK. 1999. A new form of Elongatoolithid dinosaur eggs from the Lower Cretaceous Shahai Formation of Heishan, Liaoning Province. Verteb PalAsiat. 37(4):278–284.

Zhao ZK. 1979. Discovery of the dinosaurian eggs and footprint from Neixiang County. Henan Province Vertebrata PalAsiatica. 17(4):304–311. Chinese with English Abstract.

Zhao ZK. 1993. Structure formation and evolutionary trends of dinosaur eggshells. In: Kobayashi I, Mutvei H, Sahni A, editors. Structure, formation and evolution of fossil hard tissues. Tokyo: Tokai University Press; p. 195–212.

Zhao ZK, Jiang YK. 1974. The Microstructrue of dinosaur eggs from Laiyang county, Shandong Province. Sci China Earth Sci. 1:63–72. Chinese.

Zhao ZK, Mao XY, Chai ZF, Yang GC, Kong P, Ebihara M, Zhao ZH. 2002. A possible causal relationship between extinction of dinosaurs and K/T iridium enrichment in the Nanxiong Basin, South China: evidence from dinosaur eggshells. Palaeogeogr Palaeoclimatol Palaeoecol. 178:1–17.

Zhao ZK, Mao XY, Chai ZF, Yang GC, Zhang FC, Yan Z. 2009. Geochemical environmental changes and dinosaur extinction during the Cretaceous-Paleogene (K/T) transition in the Nanxiong Basin, South China: Evidence from dinosaur eggshells. Chin Sci Bull. 54(5):806–815.

Zhao ZK, Wang Q, Zhang SK. 2015. Palaeovertebrata Sinica, volume II, amphibians, reptilians, and avians, Fascicle 7, Dinosaur eggs. Beijing: Science Press; p. 1–172. Chinese.

Zhao ZK, Zhang SK, Wang Q, Wang XL. 2013. Dinosaur diversity during the transition between the middle and late parts of the Late Cretaceous in eastern Shandong Province, China: evidence from dinosaur eggshells. Chin Sci Bull. 58(36):4663–4669.

Zhou SQ, Feng ZJ, Zhang GJ. 2001. Oolithias assemblages in Henan Province and its age significances. Geoscience. 15(4):362–369. Chinese with English Abstract.