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New type of dinosaur eggs from Yiwu, Zhejiang Province, China and a revision of *Dongyangoolithus nanmaensis*

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Abstract A new type of dinosaur egg, which is remarkable for the roughly paralleled, wavy and branched clefts on the outer surface, was recovered from Yiwu, Zhejiang Province, China. The extraordinary ornamentation indicates that the eggs do not belong to any known oofamilies. Interestingly, they share the following eggshell micro-features with *Dongyangoolithus nanmaensis*, which was previously assigned to the Dendroolithidae: branched clefts on the outer surface of the eggshell and eggshell unit assemblages separated by large cavities. Due to these similarities and the nearness of their localities and similar horizons, the new type of dinosaur eggs from Yiwu and *D. nanmaensis* likely represents a new oofamily, Dongyangoolithidae. Based on the differences in shape between the eggshell unit assemblages and clefts of the new type of dinosaur eggs and *D. nanmaensis*, we erect a new oogenus and a new oospecies, *Multifissoolithus chianensis*. The new oofamily reported here shows a close relationship with *Spheroolithus* in Spheroolithidae and an intermediate pattern of gas exchange systems.

Key words Jinqu Basin, Yiwu, Zhejiang; late Early Cretaceous; Dongyangoolithidae, *Multifissoolithus*

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1 Introduction

Yiwu City is located on the eastern margin of the Jinqu Basin, which is the largest Cretaceous basin in Zhejiang Province. Dinosaur bone and egg fossils were discovered in different sections of the Jinqu Basin (Dong, 1979; Lü et al., 2008; Yu et al., 2010). As early as 1993, dinosaur egg fossils were recovered from Yanxi Village, Fotang Town, Yiwu City. Since then, dinosaur eggs, tracks, and even bones have been discovered. Most of them were collected by the Yiwu Museum or protected *in situ*. Since 2014, the staff from the Zhejiang Museum of Natural History (ZMNH) has been conducting a survey of the dinosaur fossils in

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Yiwu City based on the project "Scientific Investigation of Dinosaur Tracks in Guanyintang Village, Yiwu City". Over the course of the fieldwork, they collected more than 60 egg fossils from Shicheng Village, Chi'an Town, Yiwu City. These eggs are notable for their medium size, extraordinaryly thick eggshell and distinctive eggshell surficial features, possibly representing a new ootaxon different from all known oofamilies. However, they share some important eggshell micro-features with *Dongyangoolithus nanmaensis*, which was previously assigned to the Dendroolithidae.

2 Material and methods

An incomplete egg clutch (ZMNH M 30057) and more than 60 eggs (ZMNH M 30060, M 30061) were collected in Chi'an Town, Yiwu City after being discovered in a construction site by a farmer. The fossil eggs were well preserved, but most biological and taphonomic information was destroyed due to the unprofessional nature of the excavation. The least weathered eggshell fragments were selected for examination.

The eggshell fragments were embedded in EXAKT Technovit 7200 one-component resin and cut by an EXAKT 300CP automatic microtome. Both radial and tangential sections were prepared by grinding and polishing to a thickness of approximately 50 μm using an EXAKT 400CP variable speed grinding system with P500 and P4000 abrasive paper. The sections were viewed under normal and polarized light using a Leica DM-RX polarized light microscope. The fossil eggs and eggshell thin sections are catalogued at the ZMNH.

3 Locality and geological setting

The specimen was discovered in the outcrop of Shicheng Village，Chi'an Town, southwest of Yiwu City, Zhejiang Province, near the eastern margin of the Jinqu Basin (Fig. 1; Yu et al., 2010) and adjacent to the western margin of the Yongkang Basin. Based on 1:50000 geological map H51E018001 Nanma, the specimen was from the late Early Cretaceous Chaochuan Formation. The lacustrine Chaochuan Formation consists of purplish sandstone with interbedded igneous rock (Bureau of Geology and Mineral Resources of Zhejiang Province, 1989). The new egg fossil site presents brown, red pelitic siltstones with sandy conglomerate. The bed is nearly horizontal with faint bedding. The gravels in the rock show a high degree of roundness and poor sorting. Some of them can be up to 8 cm in diameter with a grayish white appearance. The whole lithology represents a strong hydrodynamic environment and possibly a flooded fan deposit. The Chaochuan Formation was previously assigned to the late Late Cretaceous (Ding et al., 1987; Bureau of Geology and Mineral Resources of Zhejiang Province, 1989; Ma, 1994,1997), but some isotope age data (Xing et al., 1999, 2004; Luo and Yu, 2004), fossil comparison and stratigraphic correlation (Yu and Xu, 1999; Cai and Yu, 2001; Jin et al., 2007; Wan et al., 2007; Ding et al., 2010; Zheng et al., 2012; Azuma et al., 2013; Jin, 2013) categorized it as from the early Late Cretaceous. In the latest stratigraphic research (Li

et al., 2018), isotope dating of volcanic rocks from the Chaochuan Formation yields an age estimation of 119–104 Ma, indicating the Chaochuan Formation in this study area is similar to other Chinese late Lower Cretaceous groups in age (Li et al., 2014; Ma et al., 2016; Li et al., 2018).

Several dinosaur bones and dozens of egg fossils have been recovered from the Jinqu Basin, such as *Dongyangosaurus sinensis* (Lü et al., 2008) and *Chilantaisaurus zhejiangensis* (Dong, 1979), but eggs have not been reported in previous literature.

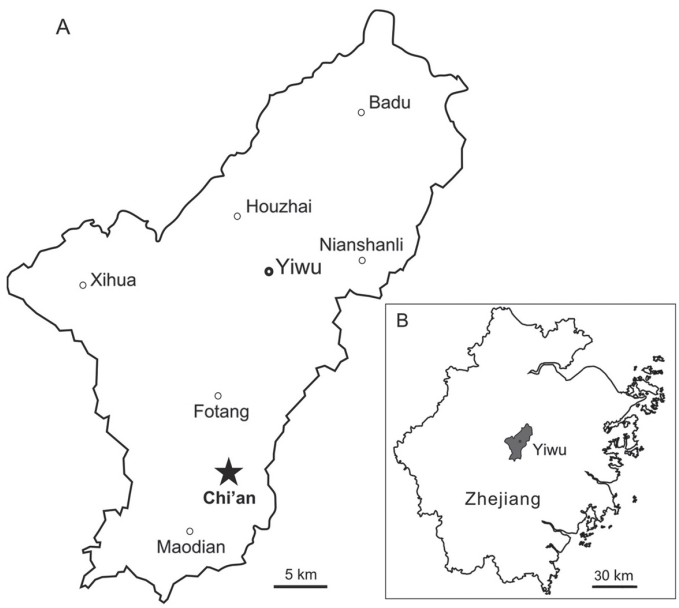

Fig. 1 Maps showing the location of Chi'an Town in Zhejiang Province

4 Systematic paleontology

Dongyangoolithidae oofam. nov.

Etymology From the type oogenus *Dongyangoolithus* Jin, 2013.

Type oogenus *Dongyangoolithus*.

Included oogenera *Dongyangoolithus*, *Multifissoolithus* oogen. nov.

Distribution and age Dongyang and Yiwu cities, Zhejiang Province, China; Lower Cretaceous.

Diagnosis Spherical to oval eggs. Smooth outer surface with branched clefts and round pores. Columnar or fan-shaped eggshell unit assemblages separated by large cavities in radial sections.

***Multifissoolithus* oogen. nov.**

Etymology *Multifiss*-, in Latin, means 'multi-fracture', in reference to the clefts on outer surface of eggs; - *oolithus* (masculine), in Greek, means 'egg stone'.

Type oospecies *Multifissoolithus chianensis* oosp. nov.

Locality and horizon As for the type and only oospecies.

Diagnosis As for the type and only oospecies.

***Multifissoolithus chianensis* oosp. nov.**

(Figs. 2–4)

Etymology 'chian' refers Chi'an Town , the locality where the specimens were collected.

Holotype ZMNH M 30057, an incomplete egg clutch.

Referred material ZMNH M 30060, M 30061, more than 60 fossil eggs.

Locality and horizon Chi'an Town, Yiwu City, Zhejiang Province, China; Lower Cretaceous Chaochuan Formation.

Diagnosis Eggs with diameter of 8–10 cm, randomly arranged in nest. Roughly paralleled and wavy clefts on outer surface. Eggshell 3.21–3.64 mm thick, with large cavities between columnar eggshell unit assemblages. Round pores in tangential sections.

Description The incomplete clutch contains six eggs and three egg impressions. Four eggs are in direct contact with each other, while the other two are still embedded in the rock (Fig. 2A). The egg impressions are adjacent to the fully exposed eggs, showing a tight arrangement (Fig. 2A). The eggs are spherical, with diameters of 8–10 cm (Fig. 2A). There are roughly paralleled, wavy and branched clefts filled with calcite on their outer surface (Fig. 2B). These clefts extend to the inner surface of eggshell, showing a palisade microstructure in radial sections that are vertical to the clefts (Fig. 3A). However, in the radial sections parallel to the clefts, the eggshell units fuse extensively with a few cavities in the inner part of the eggshell (Fig. 3B). In other radial sections, columnar eggshell unit assemblages are separated by cavities that gradually get narrower towards the outer surface of eggshell. Horizontal accretion lines are distributed evenly throughout the eggshell (Fig. 3C). The cones are tiny on the inner surface of eggshell, and usually absent on the specimens due to weathering.

In tangential sections near the outer surface of the eggshell, polygonal eggshell unit assemblages are separated by branched clefts, showing a mosaic microstructure (Fig. 4A). Pore openings are round but rare (Fig. 4A, B). Through the outer part of the eggshell, polygonal

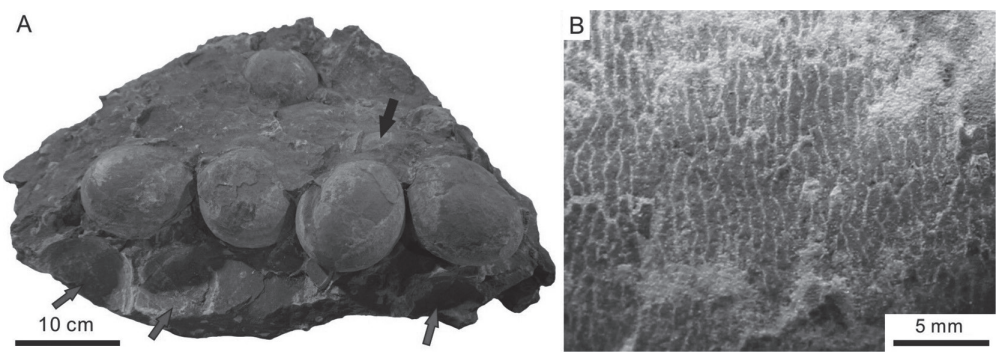

Fig. 2 Holotype of *Multifissoolithus chianensis* oogen. et oosp. nov. (ZMNH M 30057)
A. an incomplete clutch, red and black arrows indicate egg impressions and an incomplete egg respectively; B. the outer surface of an egg in the ZMNH M 30057 clutch, showing roughly paralleled and wavy clefts

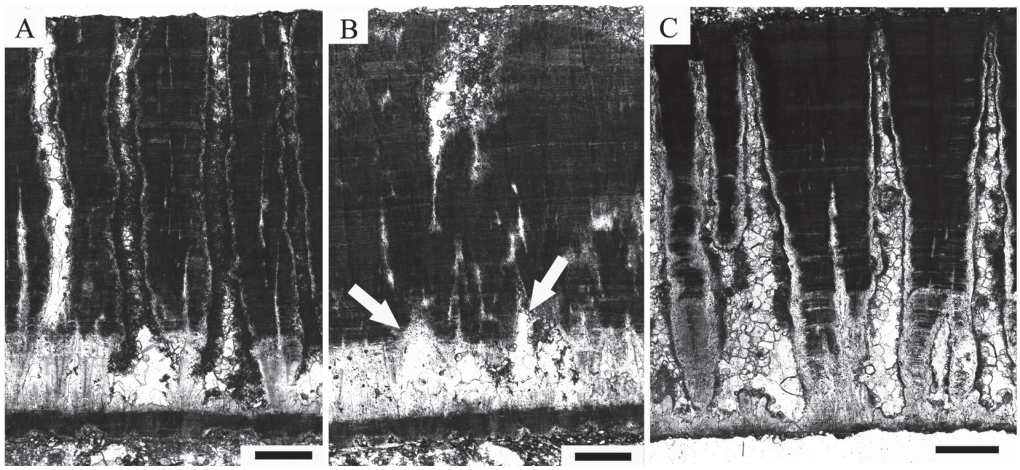

Fig. 3 Eggshell microstructure of radial sections of *Multifissoolithus chianensis* oogen. et oosp. nov. (ZMNH M 30057, holotype)

A. radial section vertical to the clefts, showing a palisade microstructure; B. radial section parallel to the clefts, the cavities in the inner part of eggshell are indicated by arrows; C. radial section unparallel to the clefts, showing the gradually narrowing cavities between columnar eggshell unit assemblages

Scale bars equal 500 μm

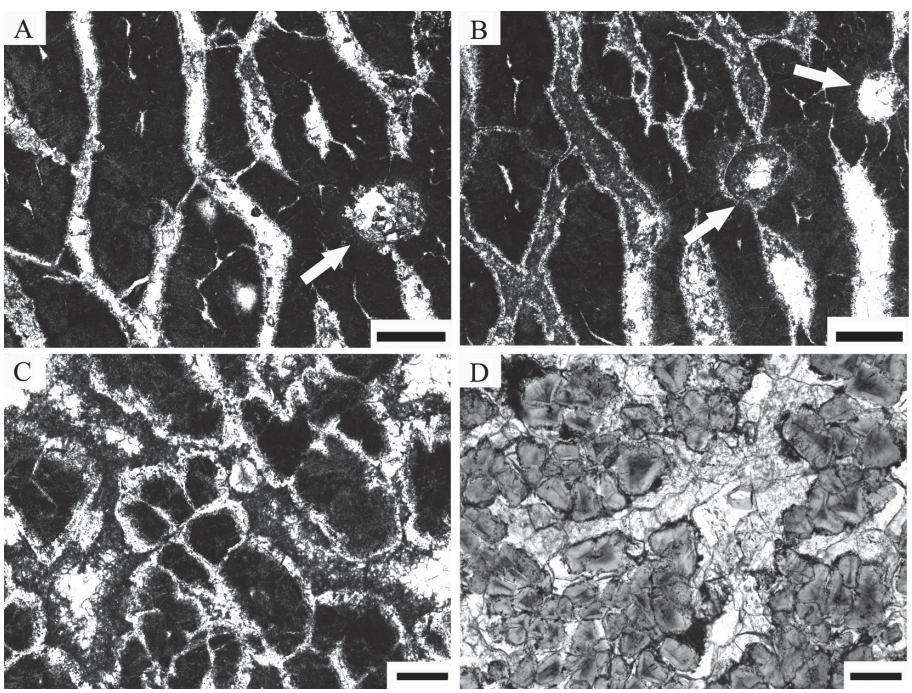

Fig. 4 Eggshell microstructures of tangential sections of *Multifissoolithus chianensis* oogen. et oosp. nov. (ZMNH M30057, holotype)

A, B. tangential sections near the outer surface (A) and through the outer part (B) of eggshell, showing the wavy and branched clefts between eggshell unit assemblages, with arrows indicating pores;

C, D. tangential sections through the inner part (C) and near the inner surface (D) of eggshell, showing isolated eggshell units with triangular cunei. Scale bars equal 400 μm in A and B and 200 μm in C and D

eggshell unit assemblages become more fragmented and the clefts become wider (Fig. 4B). Towards the inner part of the eggshell, eggshell units are separated by irregularly shaped cavities (Fig. 4C). Near the inner surface of the eggshell, eggshell units become smaller and triangular cunei appear in every eggshell unit (Fig. 4D).

Comparison Previous studies showed that only spheroolithid, stalicoolithid and megaloolithid eggshells are thicker than 3 mm (Vianey-Liaud et al., 2003; Wang et al., 2012; Liu et al., 2013; Sellés et al., 2013; Zhao et al., 2015), however these three oofamilies do not present roughly paralleled, wavy and branched clefts on the outer surface of eggs nor eggshell unit assemblages in the outer part of eggshell (Table 1). Kim et al. (2009) reported dinosaur eggs from mid-west South Korea with a similar cleft microstructure on the outer surface and assigned them to the Dendroolithidae. Unfortunately, their assignment is uncertain due to the absence of eggshell micrographs and their incomprehensive description of the eggshell microstructure. Therefore, a detailed comparative study between the eggs from Yiwu and mid-west South Korea is unavailable.

Dongyangoolithus nanmaensis, whose eggshell thickness is 2.8–3.7 mm, was previously assigned to the Dendroolithidae (Jin, 2013). The eggshell thickness, fan-shaped eggshell unit assemblages separated by large cavities in the inner part of eggshell and tiny cones are similar to the new specimens from Yiwu, but none of these features present in dendroolithid eggs. On the other hand, *D. nanmaensis* differs significantly from the new specimens from Yiwu by displaying blocky eggshell unit assemblages and irregularly branched clefts on the outer surface of eggshell. Therefore, the dinosaur eggs from Dongyang and Yiwu represent a new oofamily, Dongyangoolithidae and two oogenera, *Dongyangoolithus* and *Multifissoolithus*.

Table 1 Comparison of Dongyangoolithidae, Spheroolithidae, Stalicoolithidae and Megaloolithidae

Oofamily	Egg size (mm)	Eggshell thickness (mm)	Ornamentation	In the outer part of eggshell	
				Arrangement of eggshell units	Shape of pores
Dongyangoolithidae[1)]	(66–100)×(50–66)	2.8–3.7	Smooth with branched clefts	Forming eggshell unit assemblages	Round
Spheroolithidae[2)]	(74–99)×(67–88)	1.5–5.7	Smooth or tiny nodes separated from each other	Fusing extensively	Irregularly shaped
Stalicoolithidae[3)]	(93.6–125)×(90–123)	2.3–4.0	Smooth or tiny nodes separated from each other	Fusing extensively	Round
Megaloolithidae[4)]	120–230	1.12–4.80	Round nodes packed together	Packed together with clear boundaries	Round

Besed on: 1) Jin, 2013; this paper; 2) Liu et al., 2013; Zhao et al., 2015; 3) Wang et al., 2012; Zhao et al., 2015; 4) Vianey-Liaud et al., 2003; Sellés et al., 2013.

5 Discussion

The inner part of eggshell and the eggshell thickness indicate a close relationship between dongyangoolithid eggs and *Spheroolithus* of the Spheroolithidae. Both of them are composed

of isolated eggshell units with triangular cunei (Fig. 4D; Liu et al., 2013; Zhao et al., 2015). In the outer part of eggshell, eggshell unit assemblages fuse extensively in *Spheroolithus*, but keep isolated in dongyangoolithid eggs. Despite the difference, dongyangoolithid eggs should have the same eggshell formation mechanism as spheroolithid, dictyoolithid, faveoloolithid and dendroolithid eggs: the eggshell membrane fibers and eggshell units form simultaneously, and then additional fibers and eggshell units form repeatedly during the process of eggshell formation (Zhao, 1993; Zhao et al., 2015). However, because of the existence of clefts between eggshell unit assemblages in dongyangoolithid eggs, *Spheroolithus* could be more adaptable to arid environment due to the more compact outer part of eggshell.

The gas exchange systems of dinosaur eggshell can be categorized into pore canals (e.g. Elongatoolithidae, Prismatoolithidae, Ovaloolithidae, Megaloolithidae and Faveoloolithidae) and cavities between eggshell units (e.g. Dictyoolithidae) (Zhao, 1979, 1993, 1994; Grellet-Tinner et al., 2012; Zhao et al., 2015). In some oofamilies, such as the Dendroolithidae and Similifaveoloolithidae, large cavities are a main component of eggshell gas exchange systems, while pore canals only appear near the outer surface of eggshell (Zhao and Li, 1988; Wang et al., 2011; Zhao et al., 2015). By contrast, the gas exchange systems of the Spheroolithidae and Stalicoolithidae is mainly composed of pore canals, while cavities only exist near the inner surface of eggshell (Zhao, 1979; Wang et al., 2012; Liu et al., 2013; Zhao et al., 2015). Dongyangoolithid eggs exhibit an intermediate pattern of gas exchange systems: both pore canals and cavities exist in the outer part of the eggshell, and extend to the outer surface of the eggshell. Cavities are a main component, forming branched and wavy clefts on the outer surface of eggshell, while pore openings only appear occasionally.

6 Conclusions

The new dinosaur eggs from Yiwu, Zhejiang Province, China represent a new oogenus and a new oospecies based on following features: roughly paralleled and wavy clefts on the outer surface and columnar eggshell unit assemblages separated by large cavities. A new oofamily, Dongyangoolithidae is thus erected based on the similarities between *Dongyangoolithus nanmaensis* and the new dinosaur eggs reported in this study. Furthermore, microstructures in the inner part of the eggshell indicate that this newly erected oofamily has a close relationship with *Spheroolithus* of the Spheroolithidae. Pore canals and cavities between eggshell unit assemblages extend to the outer surface of the eggshell, representing an intermediate pattern of gas exchange systems.

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浙江义乌恐龙蛋化石新类型及对南马东阳蛋的修订

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摘要：浙江省义乌市发现了一种新类型的恐龙蛋化石，外表面上具有大致相互平行的波状分枝裂隙。这种奇特的纹饰表明这种蛋不属于已知的任何蛋科。有趣的是，它们与曾经被归于树枝蛋科的南马东阳蛋(*Dongyangoolithus nanmaensis*)有一些相同的蛋壳显微特征：外表面的分枝裂隙和被巨大空腔分隔的壳单元集合体。考虑到地点和层位都很接近，这一新类型的恐龙蛋和南马东阳蛋应被归于一新蛋科。由于这种新类型恐龙蛋的壳单元集合体及裂隙的形态不同于南马东阳蛋，因此又建立了一个新的蛋属、蛋种——赤岸多裂隙蛋(*Multifissoolithus chianensis*)。新蛋科与圆形蛋科的圆形蛋属(*Spheroolithus*)有较近的亲缘关系，还具有一种过渡型的气体交换系统。

关键词：浙江义乌，金衢盆地，早白垩世晚期，东阳蛋科，多裂隙蛋属

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