Recent Progress in the Study of Dinosaur Eggs in China

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Dinosaur eggs are a special type of vertebrate fossils. Despite their varied shapes, all dinosaur eggs are composed of eggshells, though the thickness of the shell may also vary. Dinosaur eggshells consist primarily of the mineral calcite (calcium carbonate). By studying dinosaur eggs, we can infer the reproductive system and behavior of dinosaurs and even the palaeoenvironment, palaeoclimate, palaeoecology in which they lived. Moreover, dinosaur eggs are useful for stratigraphic division and correlation as well as paleobiogeographic interpretations.

Dinosaur eggs were first reported in China by Chow (1951), based on fossil eggshells associated with the dinosaur bones in the Upper Cretaceous Wangshi Group of Laiyang County, Shandong Province. During the 1950-51 field seasons, the famous fossil skeleton of the hadrosaur *Tsintanosaurus spinorhinus* and many complete eggs and eggshell fragments were collected and described (Chow, 1954; Young, 1954). The early 1960s witnessed renewed interest in dinosaur eggs inspired by the discovery of a rich collection of them in Nanxiong Basin, Guangdong Province. It also stimulated a more intense search for fossil eggs in other regions. Up to now, numerous dinosaur egg localities have been reported in 14 provinces throughout China. However, a systematic study of Chinese dinosaur eggs is still absent, and many specimens remain uninvestigated.

Dinosaur eggs and eggshells are never structurally connected with the skeletons; this makes it difficult to assign a certain egg to a certain dinosaur taxon. An exception only occurs when the eggs contain embryonic skeletons or the nest contains eggshells and hatchings.

Zhao (1975) suggested a general scheme for the classification of all known dinosaur eggs. This classification involves defining groups or categories of dinosaur eggs in a hierarchical Linnean framework.

The structural characters used for this classification may be arranged into three categories, namely the macromorphological and histostructural characters of the eggs and ethological characters of the nest. Macromorphological diagnostic characters might comprise the shape and the size of the egg, the sculpturing of its outer shell surface and the thickness of the eggshell. Histostructural characters differentiating an egg taxon from another might include the basic structural units and pore canal features of the eggshells, including the size, the shape and arrangement of the mammillae, cones, and columnae, and the type of pore canal system; the texture of the eggshell, including the sequence and composition of its horizontal ultrastructural zones may also help distinguish a taxon from another.

Incidentally, it should be stressed that the histostructural characters must be observed in both tangential and radial sections through a dinosaur eggshell. The tangential section is especially important for distinguishing different dinosaur eggs. It is a pity, however, in practice many researchers differentiate dinosaur eggs according to the radial section only.

Dinosaur eggs and the dinosaur extinction

The “red beds” in the Nanxiong Basin of Guangdong Province are a relatively continuous sequence extending across the K/T boundary, containing dinosaur eggs in the lower layers and Paleocene mammals in the upper ones, and they seem to provide some direct evidence for interpreting the dinosaur extinction. Previously-published data from the CGY-CGD and CGT-CGF sections of the Nanxiong Basin show that the geochemical environmental changes and the dinosaur extinction in South China may have been a rather long process, instead of an instantaneous event that only lasted a few years or centuries as has often been portrayed in

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the asteroid hypothesis.

To better understand how the cause and timing of the dinosaur extinction took place, Zhao *et al*. (2009) investigated trace elements, including Ir, stable isotope composition and eggshell structures in a series of dinosaur eggshells from the third K/T section (the CGN section) in the Nanxiong Basin. Their purpose is to establish the environmental change pattern across the K/T boundary and the effect of geochemical environmental stress on dinosaur extinction, based on the geochemical signals (*e.g.*, trace elements, including Ir, and stable carbon- and oxygen-isotope composition), histostructures of dinosaur eggshells, and other data regarding stratigraphy obtained from the above-mentioned three sections (CGY-CGD, CGT-CGF, and CGN sections).

It is possible that the dinosaur extinction may be the result of a complex event or multiple ones brought about by the coincidence of global environment change marked by Ir and $\delta^{18}O$ anomalies and environmental poisoning characterized by other trace elements derived from the local source. Successive short- and long-term conditions of geochemically-induced environmental stress negatively affected the reproductive process and thus contributed to the extinction of dinosaurs.

This geochemical study of dinosaur eggshells reveals a strong influence of the environment on the elemental and isotope composition of eggshells and on the formation of pathologic eggshells. It also highlights the importance of working within a detailed stratigraphic framework. Fortunately, rather continuous outcrops of the K/T boundary interval are available for studies in several basins of China, and the current work in progress should help to test the above scenario.

Dinosaur eggs of Tiantai Basin, Zhejiang Province

In recent years, we focus on the dinosaur eggs and egg-bearing strata of the Tiantai Basin, Zhejiang Province, and compare them with the dinosaur egg taxa from several other major basins.

The Upper Cretaceous strata of the Tiantai Basin consist of the Laijia Formation and the overlying Chichengshan Formation. Detailed studies of stratigraphic sections were carried out, along with surveys of dinosaur egg localities, to accurately locate dinosaur egg horizons. Although dinosaur eggs are present in the upper beds of the Laijia Formation, they are more abundant in the second member of the Chichengshan Formation. Nine laminated stuff beds were found interspersed with the red beds of both formations. $^{40}Ar/^{39}Ar$ isotope dating of the tuffs indicates an age of 98.3Ma–91.2Ma, corresponding to the early Late Cretaceous (Cenomanian-Turonian). This helps to establish a preliminary dinosaur egg taxon sequence.

Based on the dinosaur egg taxonomy suggested by Zhao and integrating macromorphological and microstructural characters of dinosaur eggs and eggshells, seven oofamilies, twelve oogenera, and fifteen oospecies have been recognized in the Tiantai Basin. Many of them are new taxa (Wang *et al*., 2010a, b).

In addition, the classification of dinosaur eggs is partially revised. For example, *Macroelongatoolithus* (Fig. 1) is separated from Elongatoolithidae, and, together with the new oogenus *Megafusoolithus* (Fig. 2), forms a new oofamily Macroelongatoolithidae (Wang *et al.*, 2010a).

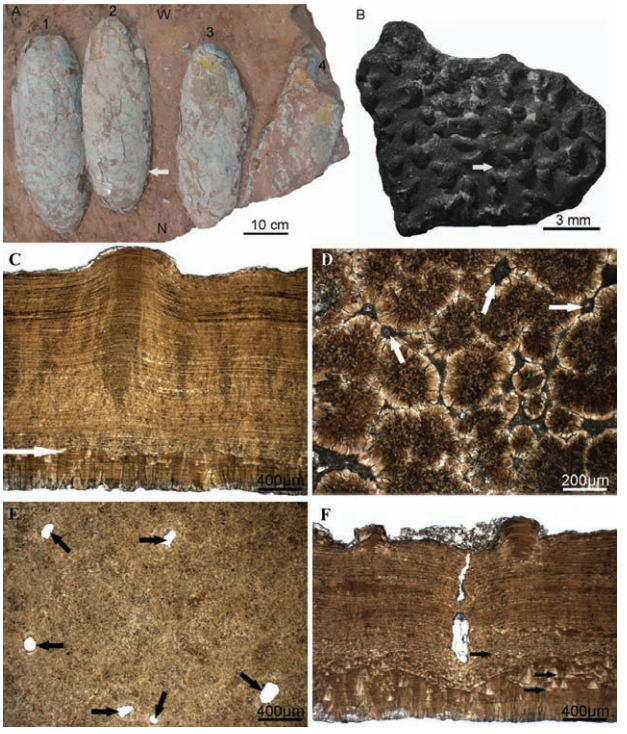

Fig. 1 *Macroelgongatoolithus xixiaensis.*
A: Fossil eggs of *Macroelgongatoolithus xixiaensis* (TTM15 housed in the Tiantai Museum, Zhejiang Province). N and W, inner and outer sides of nest; 1–4, numbers designating individual eggs.
B: Nodular ornamentation on the outer surface of the eggshell, with arrow indicating pores on the outer surface.
C–F: Microstructure of the eggshell. C, Radial section through the eggshell, showing the boundary between the cone layer and the columnar layer (arrow); D, Tangential section through the middle part of the cone layer, showing variable sizes of round and elliptical cones (arrows indicate pores); E, Tangential section through middle part of the columnar layer, showing round and elliptical pores (arrows); F, Pathologic eggshell structure, showing multi-layered cones and disorderly crystallines in the lower part of the columnar layer (arrows).

The dinosaur egg taxa of the Tiantai Basin are relatively primitive, mainly consisting of faveoloolithids and dictyoolithids, which is consistent with the geological age of the basin. The faveoloolithids are the dominant

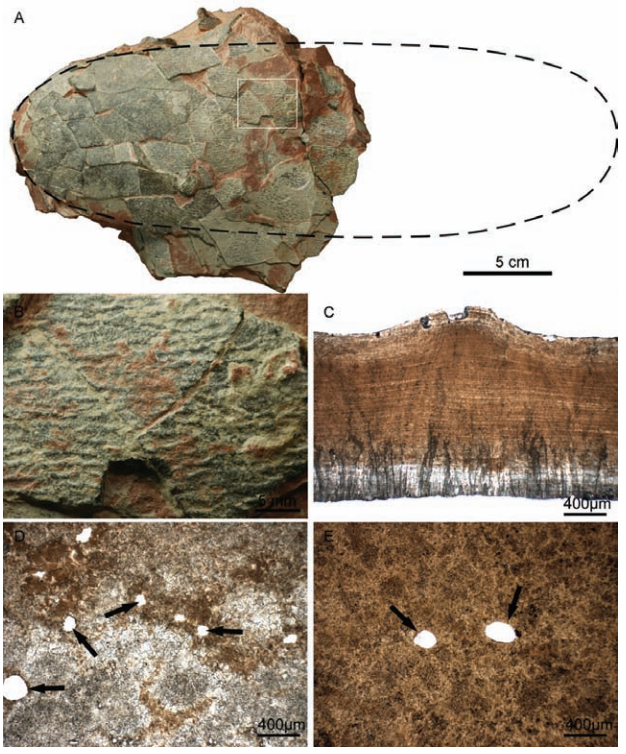

Fig. 2 *Megafusoolithus qiaoxiaensis.*
A: Holotype of *Megafusoolithus qiaoxiaensis*, showing the restored outline of a complete egg. B: Ridged ornamentation on the outer surface (enlargement of the part of eggshell within the box marked in A). C: Radial section of an eggshell. D: Tangential section through the middle part of the cone layer, showing round and elliptical cones (arrows indicate pores). E: Tangential section through the middle part of the columnar layer, showing round and elliptical pores (arrows).

group in the Laijia Formation, whereas the stalicoolithids and macroelongatoolithids are the major taxa in the lower member of the Chichengshan Formation, and the faveoloolithids and dictyoolithids are characteristic of the upper member of the Chichengshan Formation.

Comparisons between the dinosaur eggs of the Tiantai Basin and those from other basins indicate that the Tiantai Basin is similar in its oofauna to the Xixia Basin, but different from the Laiyang Basin, which itself is more similar to the Nanxiong Basin. Based on biostratigraphic and isotopic dating, China's Late Cretaceous dinosaur eggs can be divided into four preliminary assemblages, including the Tiantai Basin's dinosaur eggs (assemblage 1) representing the early Late Cretaceous dinosaur egg taxa, the Nanxiong Basin's eggs (assemblage 4) representing the late Late Cretaceous, while the eggs of the Xixia Basin and the Laiyang Basin (assemblages 2 and 3) are intermediate and respectively represent early-middle and middle-late Late Cretaceous dinosaur egg taxa (Fig. 3).

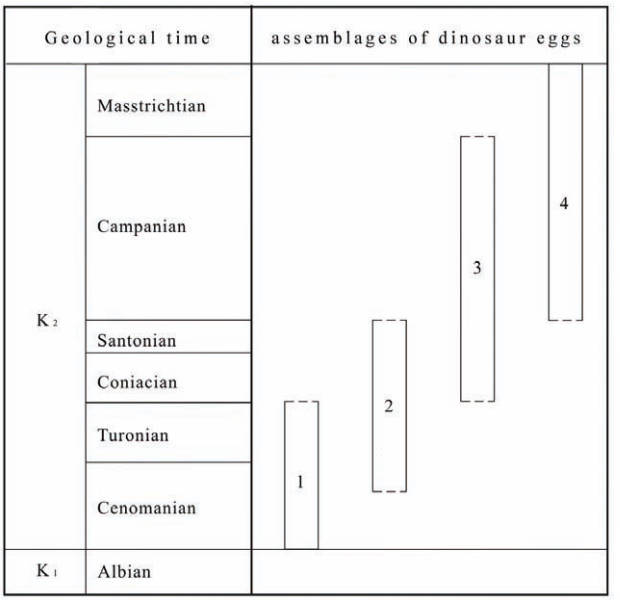

Fig. 3 Major group of assemblages of China's Late Cretaceous dinosaur eggs.
1: Tiantai Basin's dinosaur egg assemblage. 2: Xixia Basin's dinosaur egg assemblage. 3: Laiyang Basin's dinosaur egg assemblage. 4: Nanxiong Basin's dinosaur egg assemblage.

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