frontiers | Frontiers in Ecology and Evolution

TYPE Original Research
PUBLISHED 12 September 2023
DOI 10.3389/fevo.2023.1236222

OPEN ACCESS

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RECEIVED 07 June 2023
ACCEPTED 18 August 2023
PUBLISHED 12 September 2023

CITATION
Ma Z, Zhang T, Chen J, Popa ME, Li H, Li S, Zeng J and Zhang X (2023) The earliest belemnite linked with the Carnian Pluvial Episode. *Front. Ecol. Evol.* 11:1236222. doi: 10.3389/fevo.2023.1236222

The earliest belemnite linked with the Carnian Pluvial Episode

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Sinobelemnites from the Upper Triassic (Carnian, Julian 2) of the Luxi County, Yunnan Province, Southwest China are described and discussed, with two species: *Sinobelemnites maantangensis* and *Sichuanobelus luxiensis* sp. nov. *Sichuanobelus luxiensis* sp. nov. has a rostrum with a single alveolar groove along the dorsal side, with the rostral diameter increasing quickly along the rostrum cavum region. The rough rostral surface of Sinobelemnites is typical for the group. The occurrence of belemnites during the Carnian, especially during the Carnian Pluvial Episode (CPE), indicates the CPE as a drive for belemnite flourishment and preservation.

KEYWORDS

sinobelemnites, *Sichuanobelus luxiensis* sp. nov., Carnian Pluvial Episode (CPE), Southwest China, early beleminites distribution

Introduction

Belemnites (order Belemnitida), a flourishing group of Mesozoic coleoid cephalopods, appeared in the beginning of the late Triassic (Carnian) and became extinct during the Cretaceous–Paleogene event (Zhu and Bian, 1984; Fuchs and Larson, 2011a; Fuchs and Larson, 2011b; Iba et al., 2011; Iba et al., 2012). They occupied significant niches in oceanic palaeoecosystems, acting both as predators and as important prey for fish, marine reptiles and sharks (Doyle and Macdonald, 1993; Rexfort and Mutterlose, 2006; Hoffmann and Stevens, 2020). Belemnites inhabited shallow to deep waters of epicontinental seas, with a cosmopolitan presence both in the southern and northern hemispheres, extending from subtropical to polar areas (Iba et al., 2014; Dera et al., 2016). Their diversity shifts were closely correlated with environmental changes, including extinction events and climate variations (Dera et al., 2016; Hoffmann and Stevens, 2020; Neige et al., 2021).

The Sinobelemnitidae are considered the oldest belemnite group (Iba et al., 2012; Iba et al., 2014; Hoffmann and Stevens, 2020). Their earliest occurrence is recorded from Carnian strata in South China up to Japan from lower Jurassic strata (Zhu and Bian, 1984; Iba et al., 2012; Iba et al., 2014). Iba et al. (2012, 2014) also reviewed the Sinobelemnitidae along the eastern Tethyan margin, and extended the origin of the belemnites as early as the

Late Triassic, challenging the previous views related to their Jurassic origin in the western Tethys (Doyle, 1994; Weis and Delsate, 2006; Iba et al., 2012; Iba et al., 2014). The origin and palaeoecology of belemnites during pre-Jurassic times is still not fully understood. We report a new sinobelemnite species from the Carnian of southwestern China, *Sichuanobelus luxiensis* sp. nov., a species critical in understanding the early evolution of belemnites, and by extension, the biological shifts of marine ecosystems during the Carnian.

Geological settings

The studied outcrop occurs in the western transitional region between the Yangtze Carbonate Platform and the Nanpanjiang Basin, along the South China Block. During the Permian and Triassic, the Nanpanjiang Basin was represented by a deep-marine embayment, bordered along its western, northern, and northeastern sides by the Yangtze Carbonate Platform, a vast shallow-marine, carbonate platform that stretched across the South China Block (Minzoni et al., 2013). During the Late Triassic, the South China Block was located in eastern Tethys at ~20°N. The deep-waters of the Nanpanjiang Basin opened to the east into the Panthalassa Ocean (Enos et al., 1998; Figure 1A), with Carnian marine strata well developed and widely exposed in the western transitional region, with continuous sedimentary successions, including the topmost sequences of the Yangliujing, Zhuganpo, Wayao, and Laishike formations respectively (Yunnan Geological Survey, 1975; Guizhou Geological Survey, 2013).

The belemnites reported herein were collected from the siltic sandstones of the Wayao Formation, Baishui section, Luxi County, Yunnan Province, SW China. The Baishui section is located in the Xing'an village near Baishui town, Luxi County (coordinates: 24.644933°N, 103.828144°E, Figure 1B). The Wayao Formation (also known as the Wayao Member of the Falang Formation or as the Xiaowa Formation) is famous for its Guanling biota, yielding a rich marine reptile fauna and exceptional fossils of pelagic crinoids (Wang et al., 2008). Due to tectonic and depositional factors, the Wayao Formation gradually thickens from southeast to northwest, along the margin of the Nanpanjiang Basin (Minzoni et al., 2015).

At the Baishui section, the Wayao Formation can be divided in two parts:

a. the lower sequence, 3.6 m thick, beginning with black, calcareous shales interlayered with mudstones, with frequent fossils such as ceratitid ammonoids (*Trachyceras multituberculatum*), bivalves (*Halobia* sp.), crinoids (*Traumatocrinus hsui*), and less frequent gastropods (*Anulifera yunnanensis*);
b. the upper part, dominated by a siltic sandstone, with well preserved fossils such as ceratititd ammonoids (*Austrotrachyceras triadicum* and *Yakutosirenites armiger*), bivalves (*Halobia* sp.), crinoids (*Traumatocrinus hsui*), belemnites (*Sichuanobelus luxiensis* n. sp. and *Sinobelemnites maantangensis*), and gastropods (*Anulifera yunnanensis*) (Ma et al., 2023).

The new specimens were collected from the base of the upper part, about four meters above lower boundary of the unit (Figure 1C). Based on the occurrence of *Austrotrachyceras triadicum* and *Yakutosirenites armiger*, the age of the belemnites is assigned to Carnian (Julian 2).

The Carnian Pluvial Episode in South China

The Carnian Pluvial Episode (CPE), recognized as one of the most significant global climate events during the Triassic period, has garnered considerable attention in the field of geology in recent years (Dal Corso et al., 2015; Jin et al., 2015; Dal Corso et al., 2018; Dal Corso et al., 2020; Zeng et al., 2022). This event caused a substantial amount of rainfall within a short period, effectively ending the long-standing aridity that characterized the Triassic (Zeng et al., 2022). On land, sedimentary characteristics across Europe underwent a transition from widespread evaporitic salt lake and sabkha environments to fluvial and deltaic facies (Kozur and Bachmann, 2010), resulting in

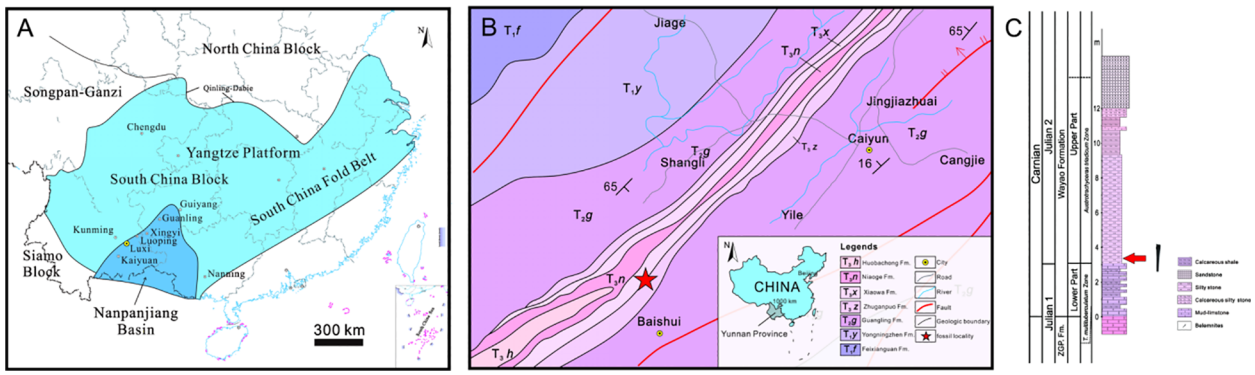

FIGURE 1
(A) Palaeogeographic reconstruction of study area during the Late Triassic interval (modified from Enos et al., 1998). **(B)** Geological map of the Luxi area and the locality with Sinobelemnites (modified from Yunnan Geological Survey, 1975). **(C)** Stratigraphic column of the Wayao Formation showing the distribution of Sinobelemnites at localities in the Luxi area.

the formation of exceptionally large deltas during this time period in locations such as Norway (Klausen et al., 2019). In shallow marine, carbonate growth was interrupted by abundant terrigenous input, leading to a crisis for carbonate factories within the Tethys realm (Hornung and Brandner, 2005; Hornung et al., 2007; Jin, 2019). In deepwater settings, sea level rise triggered extensive deposition of chert limestone followed by a transient increase in the interface depth between chert limestone and carbonate compensation depth (Rigo et al., 2007; Sun et al., 2016). Additionally, the CPE was also a biotic turnover or extinction event (Simms and Ruffell, 1989; Simms and Ruffell, 1990; Simms et al., 1995; Sepkoski, 1996). On the one hand, certain taxa exhibited significant extinction rates, including conodonts, ammonoids, bivalves, crinoids, and bryozoans (Simms and Ruffell, 1989; Simms and Ruffell, 1990; Simms et al., 1995; Bambach, 2006), as well as terrestrial flora and fauna (Benton, 1991; Seyfullah et al., 2018). On the other hand, certain significant taxa emerged during or shortly after the CPE, including mammals, crocodylomorphs, and turtles (Li et al., 2008; Pott et al., 2008; Dal Corso et al., 2020; Funston et al., 2022), while dinosaurs and Rhynchocephalia underwent a radiation event in this interval (Benton et al., 2018; Bernardi et al., 2018; Dal Corso et al., 2020).

CPE has been also well recorded in Yangtze Carbonate Platform and in the Nanpanjiang Basin (Sun et al., 2016; Shi et al., 2018; Jin et al., 2020). The Ma'antang Formation in Sichuan Province, Yangtze Carbonate Platform, and the Wayao Formation, in Guizhou Province, Nanpanjiang Basin, record CPE influences. The Wayao Formation is dominated by black shales and by dark, thin-bedded limestones and mudstones, with rare benthic representatives (Wang et al., 2008; Minzoni et al., 2015; Ma et al., 2018). The lithological facies and absence of a benthic assemblage indicate an anoxic environment during the deposition of the Wayao Formation. Multiple negative carbonate isotope excursions and the lack of carbonate deposition in Wayao Formation were triggered by the CPE (Sun et al., 2016). The Ma'antang Formation yields marine carbonates with at least three siliciclastic interlayers in its lower succession and marine silts and sandstones with bioclastic limestone interlayers to its upper part (Shi et al., 2018). Based on lithological, biostratigraphical and on stable isotopes (Carbon and Oxygen), it was demonstrated that the Ma'antang Formation was deposited during the CPE (Jin et al., 2018; Shi et al., 2018).

Materials and methods

The specimens reported in this paper were collected from the Wayao Formation, preserved in shales and in silty mudstones. All photographs were taken with a Sony ILCE-7M3 digital camera with FE 24–105 mm f/4 G OSS lens. The photographs were processed with image editing software (CorelDRAW 2018 and Adobe Photoshop 2020). All five specimens illustrated and described in this study are deposited in the Southwest Petroleum University (SWPU), Chengdu, Sichuan Province, China, with the inventory numbers SWPU: JS 0001–JS 0005. The morphological terminology follows Hoffmann and Stevens (2020).

Systematic palaeozoology

Order Belemnitida MacGillivray, 1840

Family Sinobelemnitidae Zhu and Bian, 1984

Based on the diagnosis of Sinobelemnitidae made by Zhu and Bian (1984) and by Iba et al. (2015), the surface of Sinobelemnitidae are smooth, lacking any ornaments. However, the surface of specimens from the Luxi country are ornamented, with dense and small knobs. The diameter of a single, small knob is about 10 μm, growing from the rostrum to the proostracum. Besides the Sinobelemnites, similar rostral ornamentation can only be found in some large *Megateuthis* specimens, but only along lateral rostral sides (Hoffmann and Stevens, 2020). For *Megateuthis*, two main explanations were given for this type of ornamentation: a. color markings, providing camouflage coloration or muscle attachment structures (Jordan et al., 1975; Spaeth, 1983), and b. these patterns simply reflect a heterogeneous distribution of organic matter within the rostrum (Keupp, 2012; Hoffmann and Stevens, 2020). In Sinobelemnites, the small knobs cover the whole rostrum, densely and uniformly, each small knob being united by three to four minor points. This ornamentation may related to family characters, but it also could serve some special function.

Genus *Sichuanobelus* Zhu and Bian, 1984

Type species: *Sichuanobelus longmenshanensis* Zhu and Bian, 1984, from Ma'antang section in Jiangyou, Sichuan Province, China

Sichuanobelus luxiensis sp. nov.

Figure 2A

Diagnosis

Rostrum with a single alveolar groove along the dorsal side, the rostral diameter quickly increasing along the rostrum cavum region. Groove deep and V-shaped. The lateral part of rostrum slightly compressed with no lateral lines, the surface of rostrum with well arranged knobs.

Stratum tipicum

The base of the upper part of the Wayao Formation.

Locus tipicus

Baishui section in Luxi Country, Yunnan Province, Southwest China.

Material

Specimen SWPU: JS 0001 (Figure 2A).

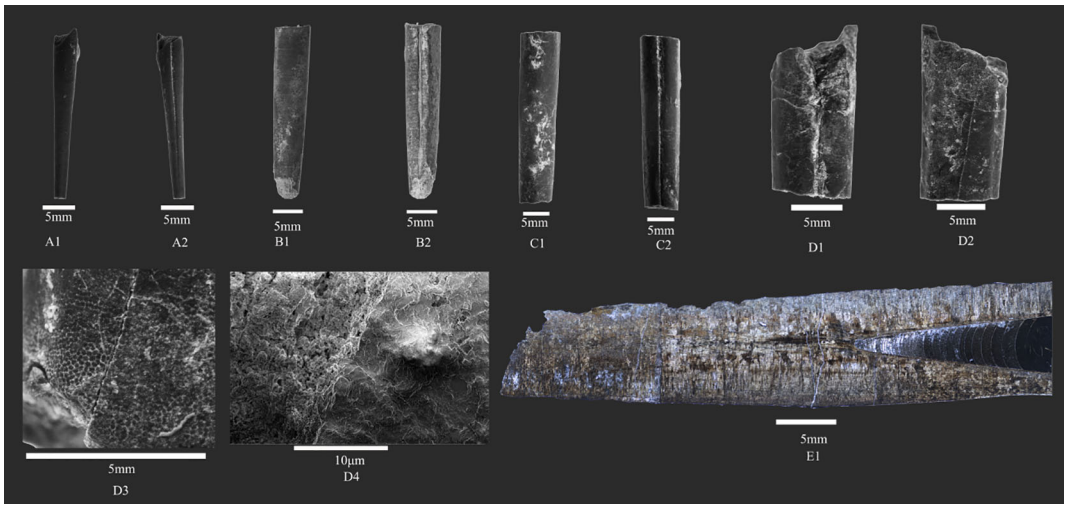

FIGURE 2
The Sinobelemnites from the lower sequence of the Wayao Formation in Luxi, Baishui section. **(A)** holotype SWPU: JS 0001 of *Sichuanobelus luxiensis*. **(A1)** Ventral view. **(A2)** Dorsal view. **(B–E)** SWPU: JS 0001–JS 0005, *Sinobelemnites maantangensis*. **(B1)** Ventral view. **(B2)** Dorsal view. **(C1)** Ventral view. **(C2)** Dorsal view. **(D1)** Ventral view. **(D2)** Dorsal view. **(D3)** details of the small knobs. **(D4)** scanning electron micrographs (SEM) of the small knobs covering the belemnite rostra. **(E1)** longitudinal section showing the organic matter enriched to the primordial rostrum region.

Holotype

SWPU: JS 0001.

Derivatio nominis

luxiensis, from the local name of the study area, Luxi.

Description

The length of the preserved rostra is 23.1 mm, medium in size. The diameter of the rostrum increases quickly along the rostrum cavum region. The largest diameter of the rostrum occurs in the anterior region. The maximum dorsoventral width (Dv) and the lateral width (Dl) are 5.0 mm and 3.0 mm, respectively, with a Dv/Dl ratio of 1.66. The rostra are covered by small knobs which become larger from the posterior area to the anterior area. The average diameter of the knobs is 10 μm. The rostrum apex is missing.

Remarks

Sichuanobelus includes three other species, *Sic. longmenshanensis*, *Sic. yangi and Sic. utatsuensis*. The *Sic. utatsuensis* from the upper Hettangian (Lower Jurassic) of Japan has a shorter rostrum with a very deep groove (Iba et al., 2012), such a feature missing in *Sic. luxiensis*. *Sic. longmenshanensis* and *Sic. yangi*, are both reported from the Carnian of the Ma'antang section in Jiangyou, with *Sic. luxiensis* n. sp. having a longer and slender rostrum, different from *Sic. longmenshanensis* and *Sic. yangi*.

Genus *Sinobelemnites* Zhu and Bian, 1984.

Sinobelemnites maantangensis Zhu and Bian, 1984
Figures 2B–E

1984 *Sinobelemnites maantangensis* Zhu and Bian, 1984, p. 307, Figure 1.

Description

The lengths of the preserved rostra vary between 20.0–35.0 mm, middle sized (Figures 2B–E), with missing apices. The largest diameter of the rostrum occurs along the alveolar region. The maximum dorsoventral width (Dv) and the lateral width (Dl) occur in samples JS0002 and JS0003, 15.0 and 12.6 mm, respectively. The Dv/Dl ratio is 1.14–1.19. The rostrum has a deep, singular, alveolar groove along the dorsal side, with two well-developed lateral lines occurring on both lateral rostral sides. All rostra are covered with small knobs which have an average diameter of 20 μm (Figures 2D3, D4). Based on longitudinal sections, the apical angle of the phragmocone is about 22° (Figure 2E1).

Remarks

This species was previously described from the Ma'antang section in Jiangyou County, Sichuan Province, Southwest China (Zhu and Bian, 1984), from the lower part of the Ma'antang Formation (Zhu and Bian, 1984). Our material from Luxi was collected from the base of the upper part of the Wayao Formation. The deep, single, alveolar groove on the dorsal side and the occurrence of lateral lines on both lateral sides of the rostra undoubtedly points to genus *Sinobelemnites*. The material has affinities with *Sin. maantangensis* Zhu and Bian 1984, with only one lateral line on each side of the rostrum, a unique character for

Sin. maantangensis. The small rostral knobs of *Sin. maantangensis* are larger than those of *Sic. luxiensis* sp. *nov.*, a species difference which could also be linked to different ontogenetic stages.

Material

Four specimens (SWPU: JS0002–JS0005, Figures 2B–E).

Discussions

The significance of the Carnian belemnites

The Sinobelemnitidae exhibit a typical belemnite morphology characterized by long rostra and a well-developed alveolar groove. However, belemnites with these characteristics were not found in Europe until the Middle Jurassic, leading to the erroneous identification of their age as belonging to the Middle Jurassic (Doyle, 1993; Doyle, 1994; Weis and Delsate, 2006). Our newly discovered specimens from Luxi county, Yunnan Province co-occurred with *Austrotrachyceras triadicum* and *Yakutosirenites armiger* provide strong evidence supporting the age of Chinese sinobelemnitids should be assigned to Carnian (Julian 2) and the Sinobelemniteidae is likely one of the most ancient clades of belemnites. Moreover, the presence of sinobelemnitids in both the northwest and southwest regions of the Yangtze Block suggests a wide distribution of sinobelemnitids in south China during the Carnian. As the Yangtze Block continues to uplift, the receding of water into the Panthalassa Ocean facilitated the migration of sinobelemnitids to the Panthalassa realm and even to the southern hemisphere, where they thrived during the early Early Jurassic (Iba et al., 2012; Iba et al., 2014; Iba et al., 2015; Figure 3).

The Carnian Pluvial Episode and the early belemnite

The earliest records of Sinobelemnitidae were made by Zhu and Bian (1984) in Jiangyou County, Sichuan Province, with all

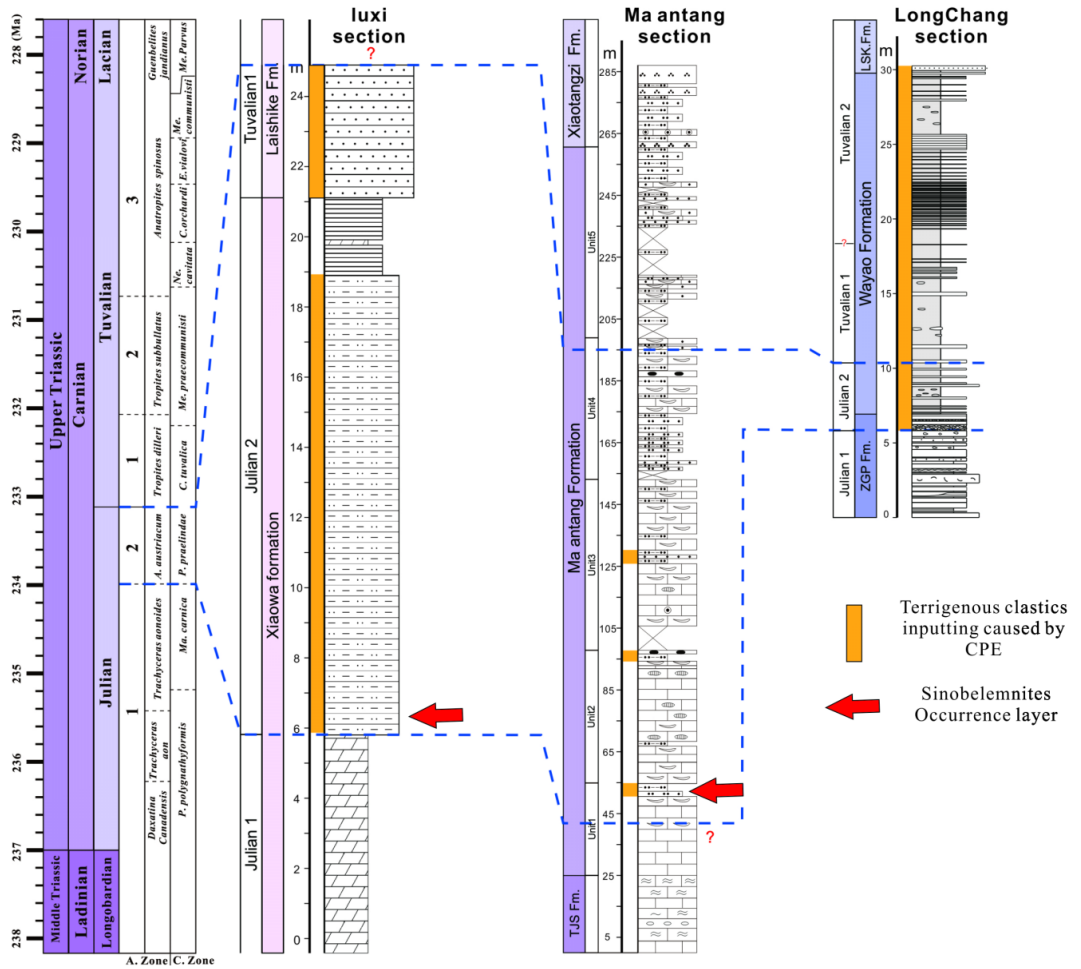

FIGURE 3
Belemnites and the Carnian Pluvial Episode records from Luxi area, Baishui section, western Nanpanjiang Basin, Ma'antang section, western Sichuan Basin (from Shi et al., 2018) and the Long Chang section (northern Nanpanjiang Basin; from Sun et al., 2016).

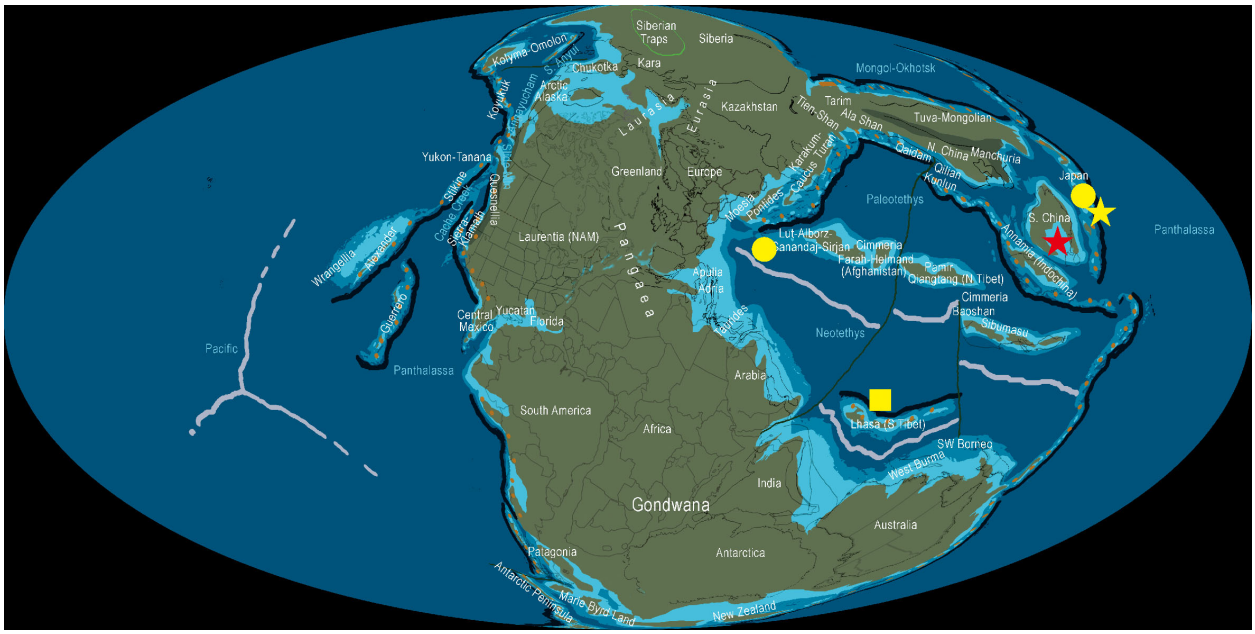

FIGURE 4
Global distributions of belemnites in the early phase of their evolution. Global palaeogeographic reconstruction for Late Triassic (220 Ma) is after Blakey (2022). Red represents the age of belemnites assigned to Late Triassic; yellow represents the age of belemnites assigned to Earliest Jurassic; star represents the localities of Sinobelemnildae; square represents the localities of putative putative; circle represents the localities of Belemnitina.

specimens collected from the middle-lower part of the Ma'antang Formation. Based on the co-occurring ammonoids, the age of the specimens was considered Carnian. Later, the Ma'antang Formation was considered to belong to Julian 2 (Shi et al., 2018; Jin et al., 2020), while the age of the Wayao Formation was considered as Julian 2 (Sun et al., 2016; Zhang et al., 2020). In our study, ammonoids such as *Austrotrachyceras triadicum*, and *Yakutosirenites armiger* co-occurred with the newly collected Sinobelemnitidae specimens, supporting the Julian 2 age.

A remarkable fact is that the Carnian belemnites occurred both in the Wayao and Ma'antang formations and the age of the strata coincides with the age of the first time terrigenous input caused by the CPE (Sun et al., 2016; Jin et al., 2018; Shi et al., 2018; Figure 4), clearly pointing to a link between the the Carnian belemnites and the CPE. The heavy rainfall transported a substantial amount of terrigenous sediments into the basin, resulting in seafloor flattening (Dal Corso et al., 2015). This process led to the expansion of the continental shelf and triggered the transition from a deep, inner carbonate platform to a shallow, nearshore sea during the Carnian period. The enlarged continental shelf provides an extensive habitat for beleminites, which thrive in this particular environment (Dzyuba, 2013; Dera et al., 2016). Meanwhile, the anoxic event triggered by the CPE (Sun et al., 2016) resulted in extensive belemnite mortality, as they were rapidly buried in sediment due to precipitation. This process facilitated the preservation of their delicate surface ornamentation on their rostrum. Although the exact explanation for this ornamentation remains unclear, this discovery provides potential evidence regarding the early morphology, ecology, and systematic evolution of belemnites.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

TZ, ZM and JZ designed the project. TZ supported the project. ZM wrote the manuscript. MP, TZ and XZ revised the draft. ZM, JC, HL and SL contributed to field work and provided specimens. ZM, JC prepared the figures. ZM, MP, JZ and TZ contributed to the discussion. All authors contributed to the article and approved the submitted version.

Acknowledgments

We are grateful to Ms. Fu Lihong (付丽红) for helping us with figures and her assistance during our field trips. This work is supported by the National Natural Science Foundation of China (No. 41972120; 42172129) and by the State Key Laboratory of

Palaeobiology and Stratigraphy (Nanjing Institute of Geology and Palaeontology, CAS) (No. 173131).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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